Georgia Tektites and Related Glasses

by

Roy S. Clarke, Jr. and E. P. Henderson

Geologic Age of the Tektite Shower and Its Associated Rocks of the Georgia Coastal Plain

by

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Introduction

Tektites are naturally occurring glassy objects, found in given, although perhaps not completely delineated, geographic areas throughout the world (Barnes, 1940, 1961; Baker, 1959). These objects have interesting shapes, are generally small, and their chemical composition indicates that they were formed at high temperature. Tektite glass is silica-rich (generally greater than 70% SiO_2), with high alumina (10-14% Al_2O_3), excess potash over soda, iron present largely in the form of reduced iron oxide, and low magnesia and lime. Although there are some similarities between tektites and obsidian (volcanic glass), there are pronounced differences. These two types of natural glass have not been shown to belong to a continuous series. In fact, the generally accepted definition of a tektite implies that it is of other than igneous origin.

The primary purpose of this paper is to discuss the Georgia tektites and their relationship to the other U. S. tektites, the Texas tektites that are generally referred to as *bediasites* and the single tektite specimen from the island of Martha's Vineyard, Massachusetts. These are the only generally accepted tektite occurrences in the Western Hemisphere. Before going to our main topic, however, a brief mention of the past literature and a listing of the classic tektite localities should prove helpful.

Brief Literature Review

Tektites have been discussed in the scientific literature since the middle of the 19th century. The excellent review papers by Barnes (1940) and Baker (1959) contain exhaustive bibliographies. The tektite problem was brought to the attention of the international scientific community by Suess' (1900) comprehensive monograph containing many excellent illustrations. Important work on tektites continued during the first half of this century. Representative of this period is the work of Dunn (1912), Fenner (1934, 1949) and Baker (1958) on Australian tektites; Lacroix's (1932) extensive studies of tektites of the Indochina area; Beyer's (1942, 1948) studies of Philippine tektites; and Spencer's (1933 a, b) discussion of the relationship of meteorite impactite to the origin of tektites.

Tektite research activity has greatly increased during the last few years. A symposium on tektites, held in Washington, D. C. in June of 1957, emphasized the many problems involved and the wide divergence of opinion as to their origin. Much of the work then in progress was reviewed and the symposium served as a stimulus to many of the more recent tektite investigations. Twelve of the papers presented were published together the following year in *Geochimica et Cosmochimica Acta* (1958, Volume 14, pages 257-379). Examples of more recent published studies are Urey (1957); O'Keefe (1960, 1961); Chapman (1960); Taylor (1961); and Cherry and Taylor (1961). Current interest in space research and the possibility that tektites are of extraterrestrial origin, or are formed as a result of impact by an extraterrestrial body, accounts for much of the present activity. Detailed petrographic, morphologic and geologic studies are being combined with data from diverse scientific disciplines in an effort to understand their obscure origin. Chemical and spectrographic analyses, aerodynamic studies, potassium-argon age determinations, and measurements of a number of physical properties are all contributing data in an attempt to bring order to a highly controversial field.

Geographic Distribution

The geographic distribution of tektite specimens is of great importance in an understanding of the nature of their occurrence. Specimens are found in a number of specific localities in a few limited geographic areas. The six areas that are generally accepted as occurrences of true tektites will be mentioned. *Australites,* specimens found in localities over the southern two-thirds of Australia, undoubtedly comprise the most important single tektite occurrence from the viewpoint of theory development. Found here are the highly prized and exceedingly rare flange specimens (Plates 1 and 2) which apparently were aerodynamically shaped and show two periods of melting. Czechoslovakian tektites, called *moldavites* after the Moldau River, occur in large numbers in Bohemia and Moravia (Plate 3). The moldavites and the Georgia Tektites are similar in many ways. Both are light colored and relatively translucent if small. All other tektites are dark, black in reflected light, and essentially opaque.

The Indochina-Malayan area has produced specimens commonly referred to as *indochinites* (Plate 4). In the Philippine Islands tektites are particularly abundant in several widely scattered places on Luzon. These specimens are referred to as *philippinites* and *rizalites* (Plates 5 and 6), and they have a number of similarities to indochinites. Tektites of the Philippine Island, Indochina area and Australia give similar and comparatively low potassium- argon ages of approximately 600,000 years (Reynolds, 1960; Gentner and Zähringer 1960a). The only tektite locality known on the continent of Africa is the Ivory Coast. The North American tektites comprise the final group. Included are the bediasites of Texas (Plates 7 and 8), the Georgia tektites and the lone specimen from Martha's Vineyard, Mass.

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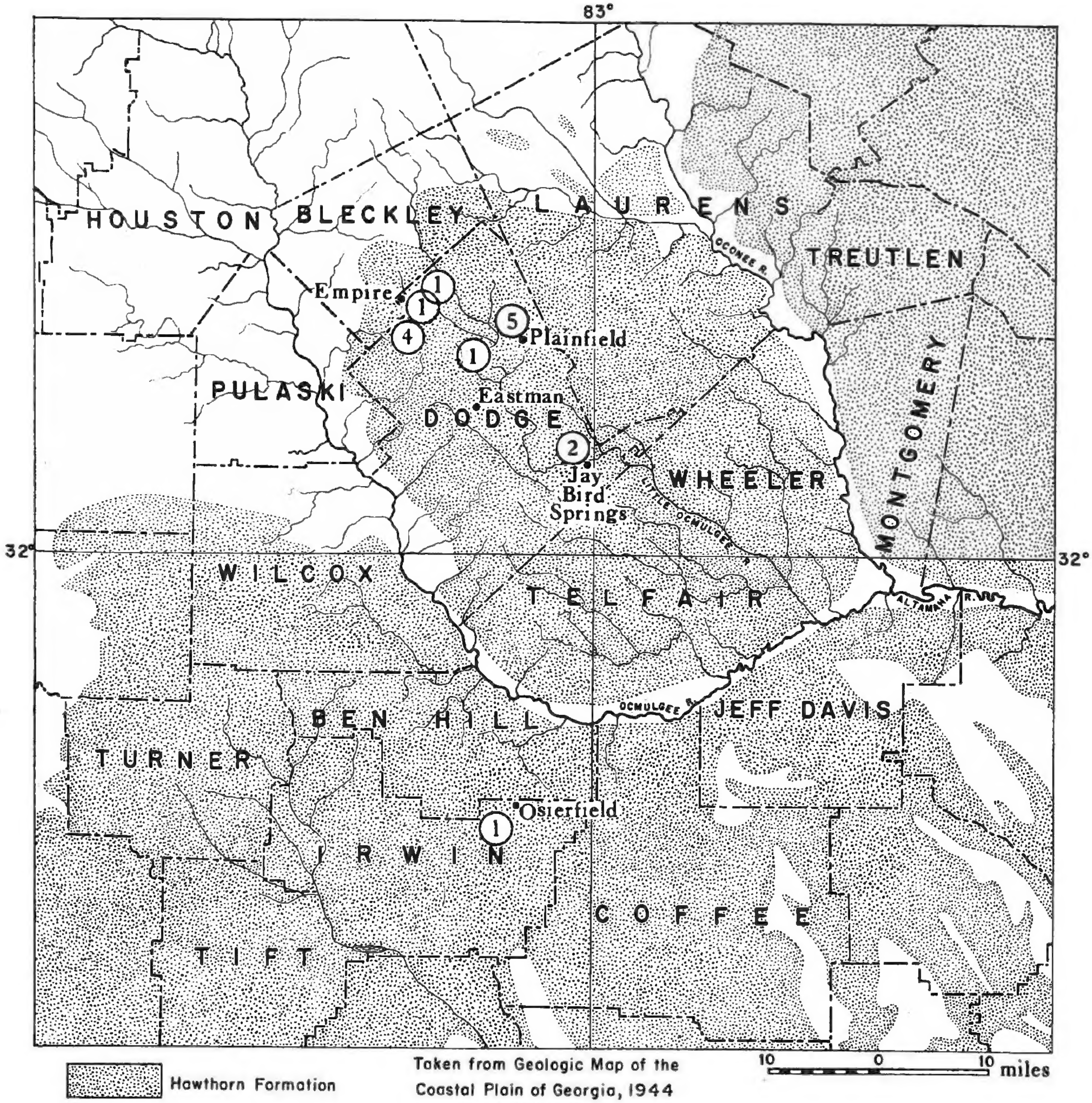
*Publication authorized by the Secretary, Smithsonian Institution.



Taken from Geologic Map of the Coastal Plain of Georgia, 1944 by C. Wythe Cooke

(1) Site and number of finds

GEORGIA TEKTITE AREA

At one time glassy pebbles from Colombia and Peru in South America were thought to be tektites but these are no longer accepted as tektites and no other proven tektite occurrence is known from this continent. The Russians, who are vigorously pursuing all extra-terrestrial studies, have thus far not reported tektite specimens from the tremendous land mass which makes up the U. S. S. R.

Origin of Tektites

The origin of tektites has been a controversial topic since they were first described. They undoubtedly result from a process that is relatively simple in outline, although tremendously complex in detail. Little agreement exists at this time even on the broad outline of the process of formation. Barnes (1958) gave a comprehensive review of theories of tektite

origin and listed six critical properties that a satisfactory theory must explain. These properties are: (1) observed chemical composition, (2) presence of lechatelierite inclusions, (3) evidence of two periods of melting in some specimens, (4) the presence of flow structure, (5) unusual shapes and limited range of sizes, and (6) their geographic distribution and age. These criteria together with results of more recent work have served to eliminate several previously considered possibilities. However, a number of possibilities remain, and in the next paragraphs we will mention some of the ideas that are currently receiving serious attention.

There are presently two main schools of thought on the origin of tektites. One group assumes that tektite parent material is terrestrial in origin, while the second group assumes an extra-terrestrial source, possibly the moon. Mechanisms involving meteorite, comet or asteroid impact, and volcanic activity can be visualized utilizing either of these source materials.

Historically the case for meteorite impact on the earth's surface was strongly supported by Spencer (1933 a, b). Dr. Harold C. Urey of the University of California is currently the leading proponent of the theory that tektites are formed from terrestrial material. He (Urey 1957) proposed that a comet impact on the earth, a fairly frequent event on the geologic time scale (one collision in 50 million years), would supply sufficient energy to melt large quantities of rock and distribute it over large areas of the earth. Dr. John A. O'Keefe of the National Aeronautics and Space Administration is the leading advocate of the surface of the moon as the source of tektites (O'Keefe 1960, 1961 a, b). He proposes that tektites form in the earth's atmosphere as ablation droplets from large blocks of glassy material that have been ejected from the moon as a result of meteorite impact. O'Keefe's calculations show that this mechanism could account for the observed specimen size range, areal distribution and restricted range of chemical compositions.

The recent work of Chao and Shoemaker and their coworkers at the U.S. Geological Survey has done much to focus attention on the importance of terrestrial meteorite impact during the geologic past. Their discovery of natural coesite, a high temperature-pressure polymorph of silica, is undoubtedly an important diagnostic aid in the recognition of large meteorite impact craters (Chao, Shoemaker and Madsen 1960; Chao, Fahey and Littler 1961; Shoemaker and Chao 1961; Cohen, Bunch and Reid 1961). The recent report from the same group of workers of the presence of iron-nickel spherules in tektites from the Philippine Islands would seem to be strong evidence for a meteorite impact origin for tektites (Chao, Adler, Dwornick, and Littler 1961). However, the recognition of these spherules does not necessarily imply the site of the impact.

The surfaces of the earth and the moon are the most likely sites for tektite producing meteorite impacts. Astronomical considerations reported by Varsavsky (1958) support the moon as a probable source of tektites. This conclusion was also reached by Chapman (1960) on the basis of aerodynamic studies and considerations of re-entry velocities. However, Cohen (1961) using data relating geographical distribution, shapes of specimens, and variation in chemical composition suggests that all the observed facts can be accounted for by the impact of large meteorites on the surface of the earth comparable to the meteorite that formed the Ries Basin in Germany (see Shoemaker and Chao 1961).

Terrestrial volcanic activity apparently is not a sufficiently energetic process to account for tektites (Urey 1957). However, there are terrestrial igneous rocks whose analysis when corrected to a water free basis are similar to the tektite analyses. Lowman's (1961) calculations show that tektites probably are not derived from any recognized terrestrial rock type and suggests they may be the result of lunar differentiation. Lowman's theory is in conflict with the conclusions of Barnes (1958), e.g. that tektites are derived either from terrestrial or extra-terrestrial sedimentary rocks.

Georgia and Martha's Vineyard Tektites

Review of Georgia and Related Tektite Studies

The identification of the first tektite specimen from Georgia was made at the Smithsonian Institution in 1938 by one of the authors (E.P.H.). The specimen had been submitted by Mr. Dewey Horne of Hawkinsville, Georgia, who had found it near Empire, Dodge County, Georgia (one mile west of Dubois, which is 2.5 miles south of Empire on U. S. Highway 23, see map of that tektite area). This specimen along with a second one, was obtained by the Smithsonian Institution (Plates 9 and 11).

Confirmation of Georgia as a tektite area was reported by Barnes and Bruce (1959). Bruce (1959) gave a general discussion of tektite finds in Georgia as well as detailed locality information on the first twelve finds. Cohen (1959) discussed Georgia tektites with particular reference to their similarity to moldavites and bediasites (see also Baker, 1960). Senftle and Thorpe (1959) measured the magnetic-susceptibility and intensity of magnetization for the Georgia tektite along with a number of other tektites. Reynolds (1960) and Gentner and Zähringer (1960 b) measured potassium-argon ages for the major tektite groups, and their calculations indicate that Georgia tektites and bediasites are of similar age (approximately 30 million years), but that moldavites are much younger (approximately 11 million years). Stair (1955 a, b, 1956) published the absorption spectra and a photomicrograph of a Georgia specimen. The measurements reported in the literature on Georgia tektites by all the writers cited above were made on one specimen, USNM-1396. Clarke and Carron (1961) reported the results of detailed investigation of this specimen, and compared it with a single specimen from a new area for tektites—the island of Martha's Vineyard, Massachusetts—recently reported by Kaye, Schnetzler, and Chase (1961). The unexpected similarity of these two specimens has led Clarke and Carron (1961) to suggest that at least some doubt as to the natural origin of these materials remains. The data on the Martha's Vineyard tektite is pertinent to an understanding of Georgia tektites, and for that reason much of it will be repeated in this paper.

New potassium-argon age determination on a Georgia tektite and the Martha's Vineyard tektite have just been reported by Dr. J. Zähringer.* His values for these two specimens of approximately 33 million years agree within experimental error.

Barnes (1956) reported a third locality that produces tekties that are chemically and physically similar to those from central Georgia. The single chemical analysis (Barnes, 1960) for these light green tektites from near Muldoon, Fayette County, Texas agrees closely with the analysis given here for the tektites from Empire, Georgia and Martha's Vineyard, Massachusetts.

The Georgia Tektite Occurrence

The few Georgia tektite specimens that are known (approximately 15) have been found in Dodge County near Empire, Plainfield, and Jay Bird Springs, and in Irwin County near Osierfield. These localities are indicated on the accompanying map of the tektite area. The numbers inside the circles indicate the number of specimens found at that

*Zähringer, J., personal communication, November 8, 1961.

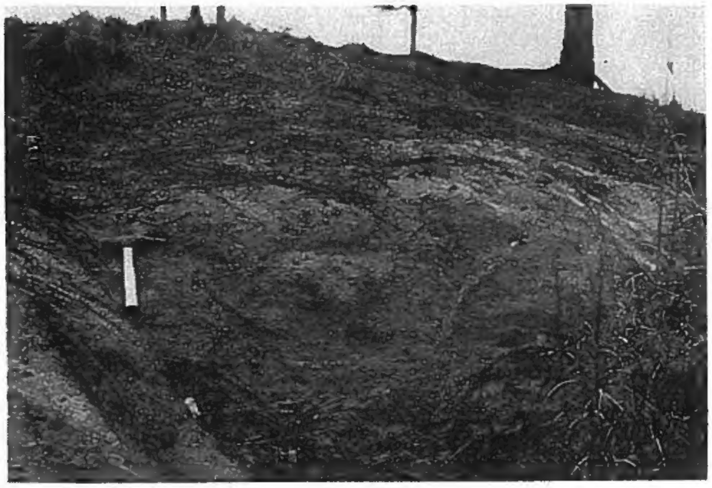


Figure 1. A gravel exposure in a gully on the south edge of the field where Mr. Dewey Horne found the first Georgia tektite specimen. The gravel near the top of this picture is only a short distance below the surface of the field. The field is about 1⅝ miles west of Dubois along a county road crossing Highway 23 and approximately 3 miles south of Empire, Georgia.

Figure 2. Gravel exposure in a road cut immediately north of the field where Georgia tektites were first found. These gravels are approximately 300 yards north of the gully in Fig. 1. The surface of the field is about 2 feet above the top of this gravel.

locality. This triangular area comprises approximately 300 square miles. All but one of the tektites were found in a narrow zone in Dodge County extending from the point of their first discovery near Empire southeastward 21 miles to Jay Bird Springs. This zone, incidentally, is essentially at right angles to the strike of the beds of the Miocene* Hawthorn formation. This complex sedimentary formation crops out over large areas of the southeastern coastal plain and underlies the entire Georgia tektite area. However, it should be emphasized that at the present state of knowledge of the geology of this area, it is impossible in most cases to say with certainly where the Hawthorn formation grades into more recent material (Cooke, 1943). The single tektite specimen found in Irwin County, near Osierfield, about 49 miles south-southeast of Empire, was found in a similar geologic setting.

All but two of the tektites came from cultivated fields on the uplands where they were exposed by the plough. They are found along with ordinary pebbles and are difficult to distinguish from pebbles until they are clean. The specimens from Jay Bird Springs were found in an area where sand and gravel from a nearby outcrop was hauled a short distance (approximately ½ mile) and spread on a parking lot, and one of the Plainfield specimens was found in or near the road. Gravel beds occur as isolated lenses throughout this area (figs. 1, 2). It should be noted however, that a relationship between gravel lenses and tektites has not been established by field data. The presence of these gravel lenses suggests that if Georgia tektites have been transported by natural processes along with these gravels, the specimens found at the southeastern end of the 21 mile zone and the single specimen from near Osierfield have moved the greatest distances.

The Hawthorn formation in the area where Georgia tektites are found is thought to be middle Miocene, perhaps 20 million years old, and possibly some of the beds in this area are much younger. The potassium-argon age that Reynolds (1960) obtained on a Georgia tektite is 32 ∓ 1.0 million years. This age presumably represents the time since the tektite was last molten. The assumption on which this "age" is based is that melting the glass results in complete degassing of argon-40, and that the loss of argon-40 after solidification has been small. Therefore, the accumulation of argon-40 from the radioactive disintegration of potassium-40 represents the time since last melting. The most probable source of error in this method is the loss of argon-40 with time due to diffusion. This means that these ages should be minimum ages and that actually the material under consideration could be much older than the calculated age. This suggests the possibility that Georgia tektites were eroded from rocks older than the Hawthorn formation and later deposited in the Hawthorn. To the west of Empire, Ga., at distances of less than 10 miles are exposures of Eocene* beds. It is possible that the Georgia tektites were originally deposited in these rocks. This would be more consistent with the 32 million year potassium-argon age. It should also be noted that drainage in this area has since Eocene times been from northwest to southeast, so perhaps these tektites have come, not from the Hawthorn formation, but from older formations to the northwest.

Tektite glass is considerably softer than the quartz and other pebbles associated with these Georgia specimens. This fact indicates that the two have not been transported far together. Tektites are also under internal strain and consequently are subject to breakage or chipping on impact. Because of these properties one would expect to find broken tektites and not the complete rather symmetrical specimens that so far have been found. (See below for discussion of morphology.)

Actually it is largely supposition that these specimens come from the Hawthorn formation. In the tektite areas this formation is complex, consisting of numerous lenses of gravel with lenses of sandy clays. It is only possible to trace a particular horizon over a relatively short distance. Furthermore, there is considerable relief in this rolling countryside and the elevations of the different tektite localities are not precisely known. More specific information about the relation of the various beds and the elevations involved is needed in order to determine if all the specimens are coming from a particular layer.

*The dates of the Miocene Period are from 25 to 13 million years (Kulp 1961).

*The dates of the Eocene Period are from 58 to 36 million years (Kulp 1961).

Plate 1. Australites

1, 2 Front and back views of specimens with partial flange from Charlotte Waters, Australia. 4X.

3 Cross section diagram of specimen shown in 4, 5.

4, 5 Front and back views of complete flange specimen. This specimen has been smoked with ammonium chloride to bring out surface features. From Glenelg, Victoria, Australia, it has been in the U. S. National Museum collection since 1903. USNM 75601. 4.89 grams, 3 X.

Plate 2. Australites

1, 2 Front and back views of specimen from New South Wales, Australia. Shape is suggestive of a drop. Ammonium chloride smoked, 2 X.

3, 4, 5 Front and back views of elongated flange specimen from Caramut, Victoria, Australia.
3, 4 ammonium chloride smoked, 5 unsmoked. USNM 2097, 1 X.

6, 7 Front and back views of core specimen from Caramut, Victoria, Australia. USNM 2097, 1 X.

8, 9 Front and back views of core specimen from Caramut, Victoria, Australia. USNM 2097, 1 X.

Plate 3. Moldavites

1, 2, 3 Front and back views of specimen from Habri, Bohemia. This 31 gram specimen is an unusually large moldavite, has the typical bottle green color and is translucent. 1, unsmoked, 2 and 3 ammonium chloride smoked, USNM 2088, 1 X.

4, 5 Front and back views of specimen from Netolitz, Southern Bohemia. Ammonium chloride smoked, 2 X.

6, 7, 8 Front and back views of a very thin specimen from Koroseky, Bohemia, 5.2 grams and a fairly common type among moldavites. 6, unsmoked, 7 and 8 ammonium chloride smoked, USNM 2071, 1X.

9, 10 This specimen from Southern Bohemia has different markings on front and back surfaces, a feature that is common to tektites in general. Ammonium chloride smoked, 2 X.

11, 12 Front and back views of a drop shaped specimen from Netolitz, Southern Bohemia. A small percentage of moldavite specimens have this general shape. Ammonium chloride smoked, 2X.

Plate 4. Indochinites

These specimens were photographed while on loan from Professor J. Orcel, Museum Historie Naturelle, Paris, France.

1, 2 Dalat Annam, Viet Nam, Ammonium chloride smoked, 1 X.

3, 4 Tan-Hai, China, ammonium chloride smoked, 1 X. The smooth curved inner surface (3) and etched outer surface (4) are a fairly common features in indochinites.

5, 6 Dalat Annam, Viet Nam, ammonium chloride smoked, 1 X. This specimen is hollow, suggestive of a pipe stem.

7-11 Tan-Hai, China, ammonium chloride smoked except for 7, 1 X. Both specimens have comparatively smooth inner surfaces and pitted outer surfaces.

12-16 Dalat Annam, Viet Nam, ammonium chloride smoked except for 12, 1 X. Specimens from this area frequently have a slaggy appearance (see 12).

An interesting discussion of indochinites has recently been given by Nininger (1961).

Plate 5. Philippine Islands Tektites

1, 2 Front and back views of an 87.5 gram specimen from Paracale, P. I. This is a large philippinite, although individuals weighing over 1000 grams are known from the Philippine Islands. Ammonium chloride smoked, USNM 2039, 2 X.

3, 4 Front and back views of a 39.4 gram specimen from Santiago, P. I. Ammonium chloride smoked, USNM 1909, 2 X.

Plate 6. Philippine Islands Tektites

1, 2 Front and back views of a 58.5 gram specimen from Santiago, P. I. Ammonium chloride smoked, USNM 1911, 2 X.

3, 4 Front and back views of a 42.5 gram specimen from Santa Mesa, P. I. The crescent shaped marking, percussion marks, suggest stream transportation. Ammonium chloride smoked, USNM 1953, 2X.

5, 6 Front and back views of 43 gram specimen from Santiago, P. I. The high concentration of small pits or bubble cavities on only one surface of a specimen is often seen in philippinites. Ammonium chloride smoked, USNM 2043, 2X.

Plate 7. Texas Tektites

Front and back views of a group of bediasites from Lee Co., Texas. Photographs illustrate typical surface features. All are ammonium chloride smoked, and have catalog number USNM 1880. 2 X magnification.

Plate 8. Texas Tektites

Front and back views of a group of bediasites from Lee Co., Texas. Photographs illustrate typical surface features. All are ammonium chloride smoked, have catalog number USNM 1880, and are at 2 X magnification.

Plate 9. Empire, Georgia Tektite, USNM 1396

This is the only Georgia tektite specimen that has undergone intensive laboratory study.

1, 2 Front and back views of specimen after slicing to remove material for analysis, ammonium chloride smoked, 2 X.

3 Portion of specimen now remaining, unsmoked, 2 X.

Note the marked similarity of etching on the two surfaces. This seems typical of Georgia tektites.

Plate 10. Martha's Vineyard Tektite

The only tektite that has been found in the North Eastern U. S. It was discovered in the summer of 1959 on a cliff at Gay Head, Martha's Vineyard, an island off the south coast of Massachusetts.

2 Surface opposite that shown in 1.

3 Photographed down deeply serrated edge. Weight 17.8 grams. USNM 2082, 3 X.

Plate 11. Georgia Tektites

1, 2 Osierfield, Irwin Co., Georgia. This specimen, belonging to the Georgia Geological Survey, is the only one to have been found outside of Dodge County. It is particularly interesting because it is nearly a perfect circle and very flat. 1, Unsmoked. 2, Same surface ammonium chloride smoked. Found in 1955, 17.8 grams, 2 X.

3, 4 A second Empire, Georgia tektite, 13.4 grams. Ammonium chloride smoked. USNM 1396, 2 X.

Plate 12. Georgia Tektites

1, 2, 3 Plainfield, Georgia, ammonium chloride smoked. Property of G. A. Bruce. 11.2 grams. 1, 2 at 2 X; 3, detail of small area with glassy spine, 10 X.

4, 5 A flattened 16.30 gram tektite found near Plainfield, Georgia by Mr. L. J. Allen. Ammonium chloride smoked, 2 X.

6, 7 A 7.05 gram tektite found near Plainfield, Georgia by Mr. L. J. Allen. Ammonium chloride smoked, 2 X.

Plate 13. Georgia Tektites

1-4 A 14.58 gram tektite found at Jay Bird Springs, Georgia in September, 1960. The specimen was found in gravel that had been spread on parking area. Gravel had been removed from farm of Mr. T. A. Bland. It was found by Mr. Will Sellers and donated to Georgia Geological Survey by Mr. Thomas E. Allen, Atlanta, Georgia.
It is the only known Georgia specimen that has a shape suggestive of a drop. (See 2). 1, 2, 3 ammonium chloride smoked 2 X. 4 is an 5 X enlargement of the thin end of the specimen taken with transmitted light. The elongated bubble is quite large for a tektite bubble and the largest that has been observed in Georgia tektites.

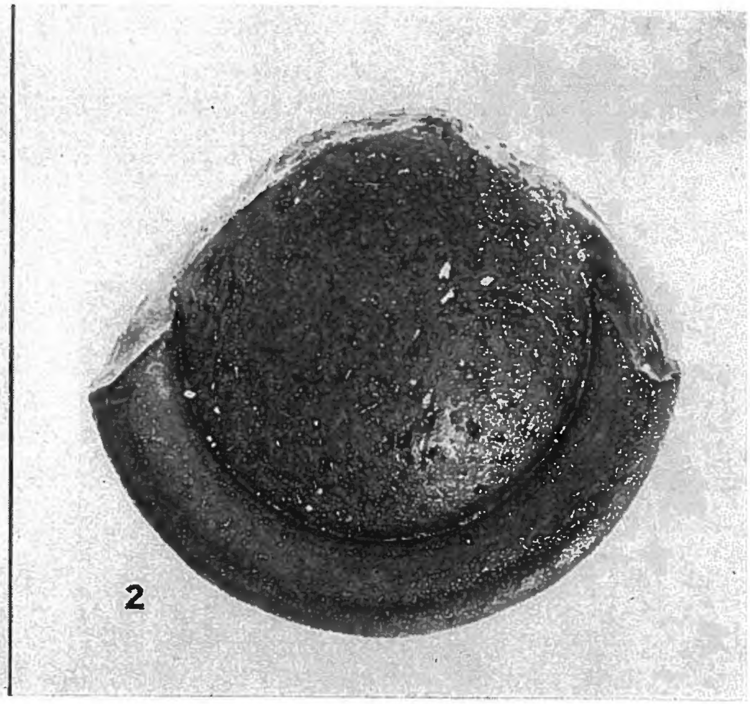
5-7 A 2.60 gram tektite found at Jay Bird Springs, Georgia in August, 1961. In the author's experience, this is the only Georgia tektite fragment known to have been found. It is also unusual in that it has a very flat surface (7). Ammonium chloride smoked, 2 X.

Plate 14. Eastman, Georgia Tektite and Martha's Vineyard Tektite Inclusion

1-4 This is the largest known Georgia tektite, 36.5 grams, belonging to Mr. W. S. Hambrick. It was found approximately 3 miles north of Eastman, Georgia in a field road, November, 1959.
1-3 Ammonium chloride smoked, 1.5 X.
4 Photograph of lechatelierite inclusions taken with transmitted light through the surface of the specimen, 12 X.

5-6 Zirconium containing inclusion in the Martha's Vineyard, Mass. tektite. 5, Photograph taken with transmitted light through the specimen showing dark central area and lighter halo, 40 X. 6, Polished surface through the dark central area in 5, at 280 X. The dark area in 5 is an aggregation of many small inclusions.

1



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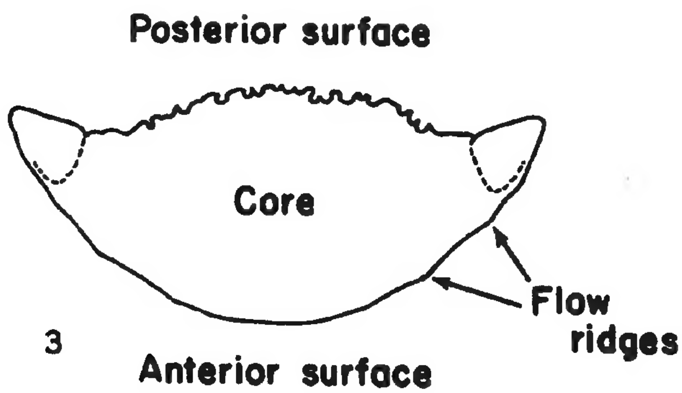

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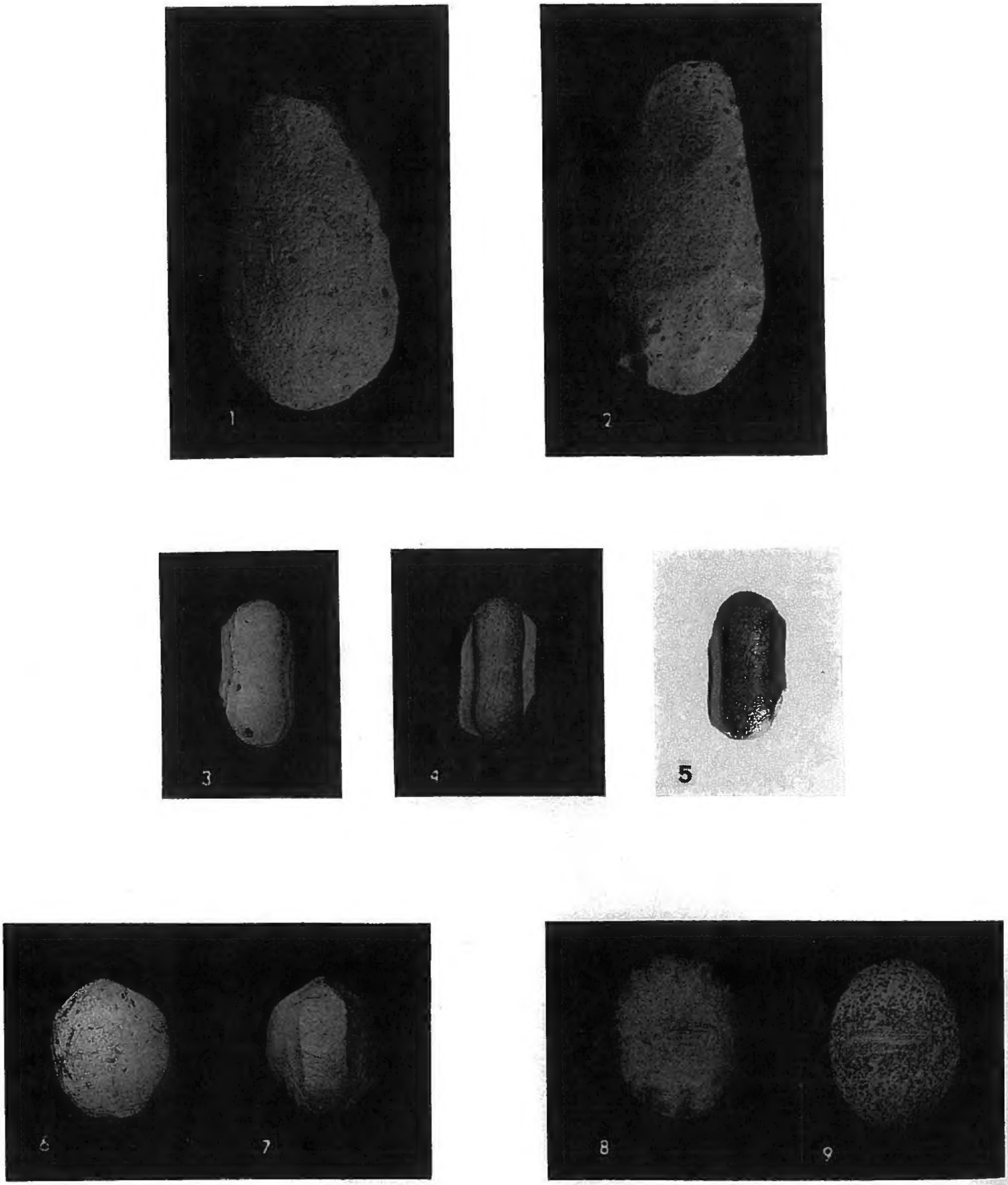
PLATE 1



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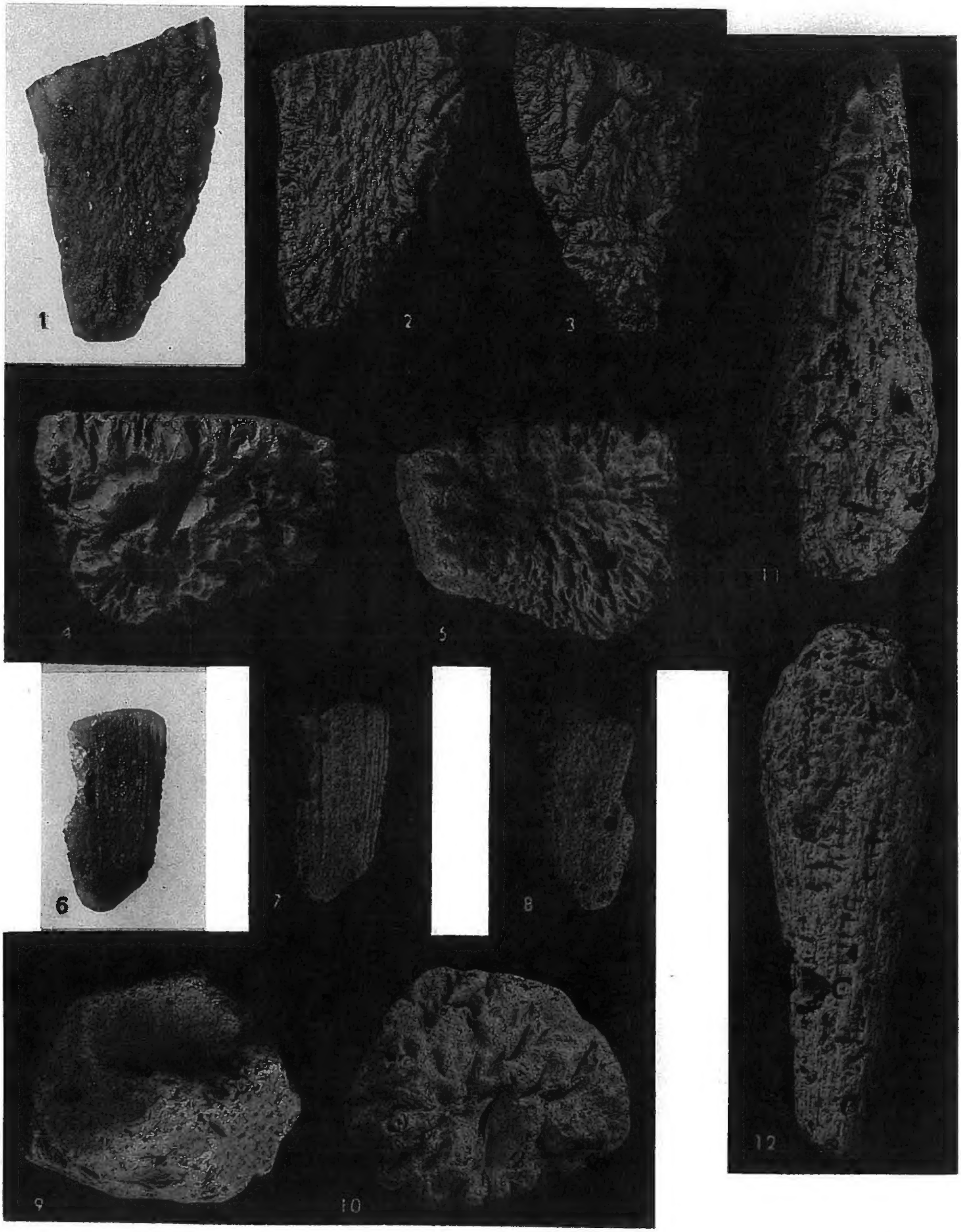

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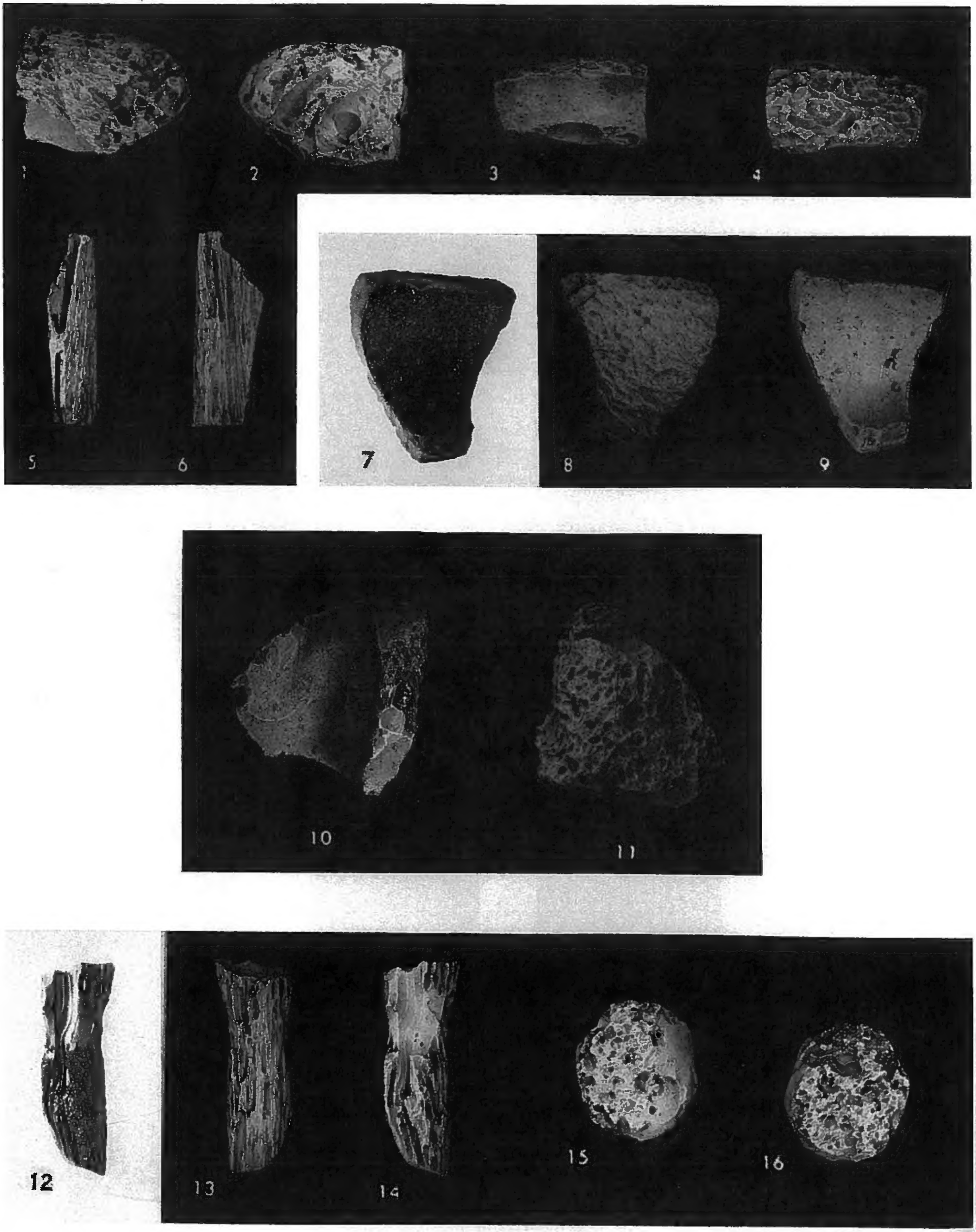

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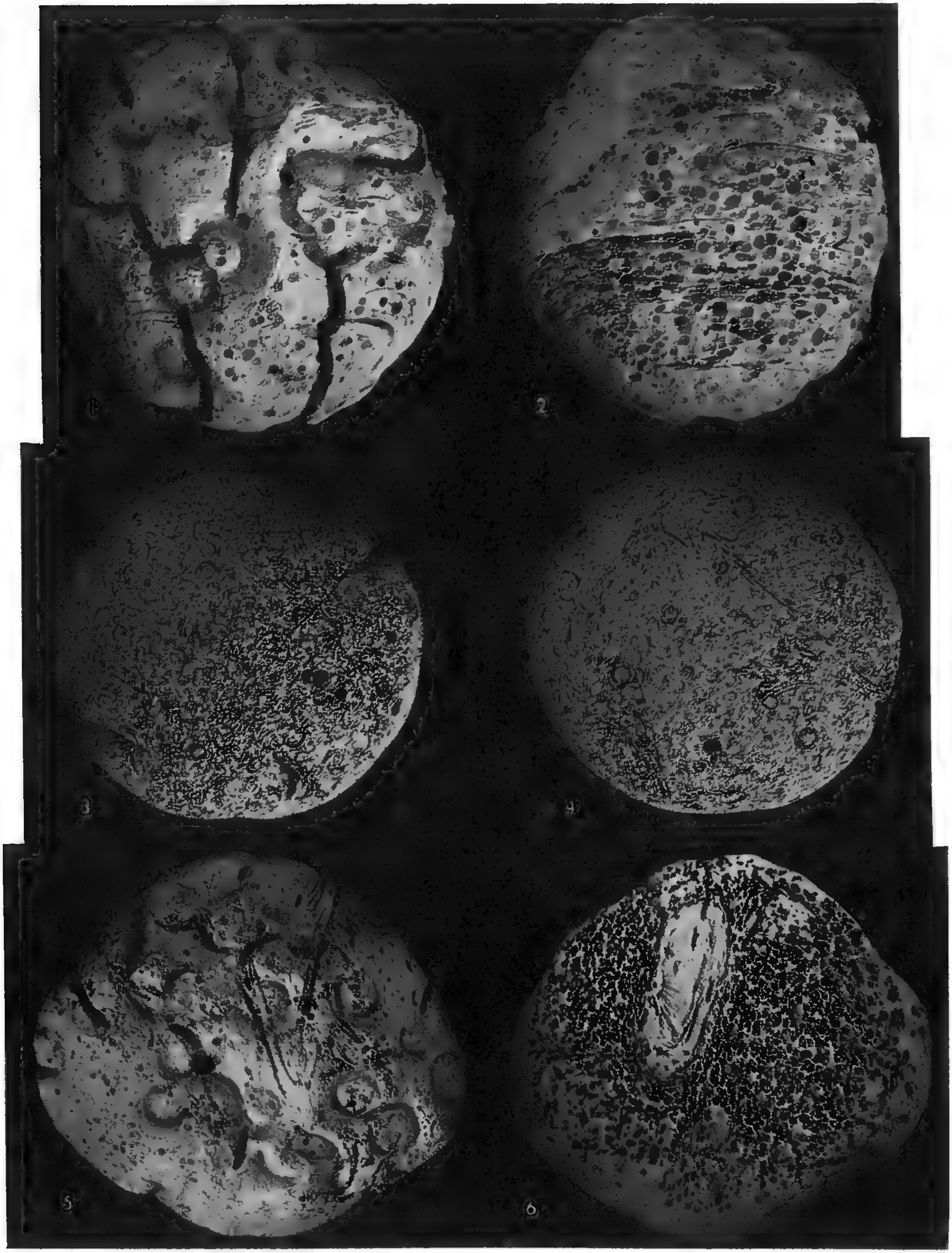

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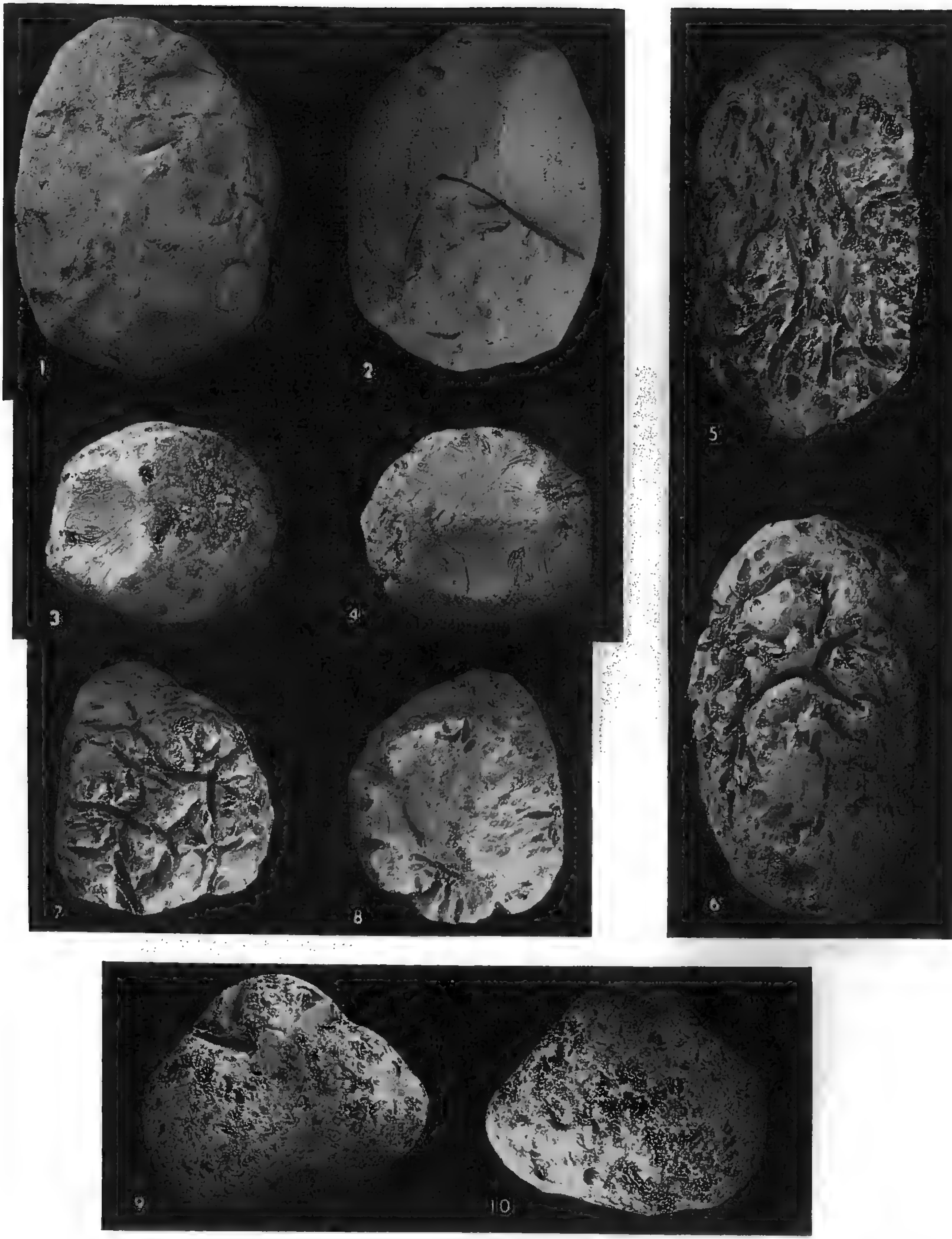
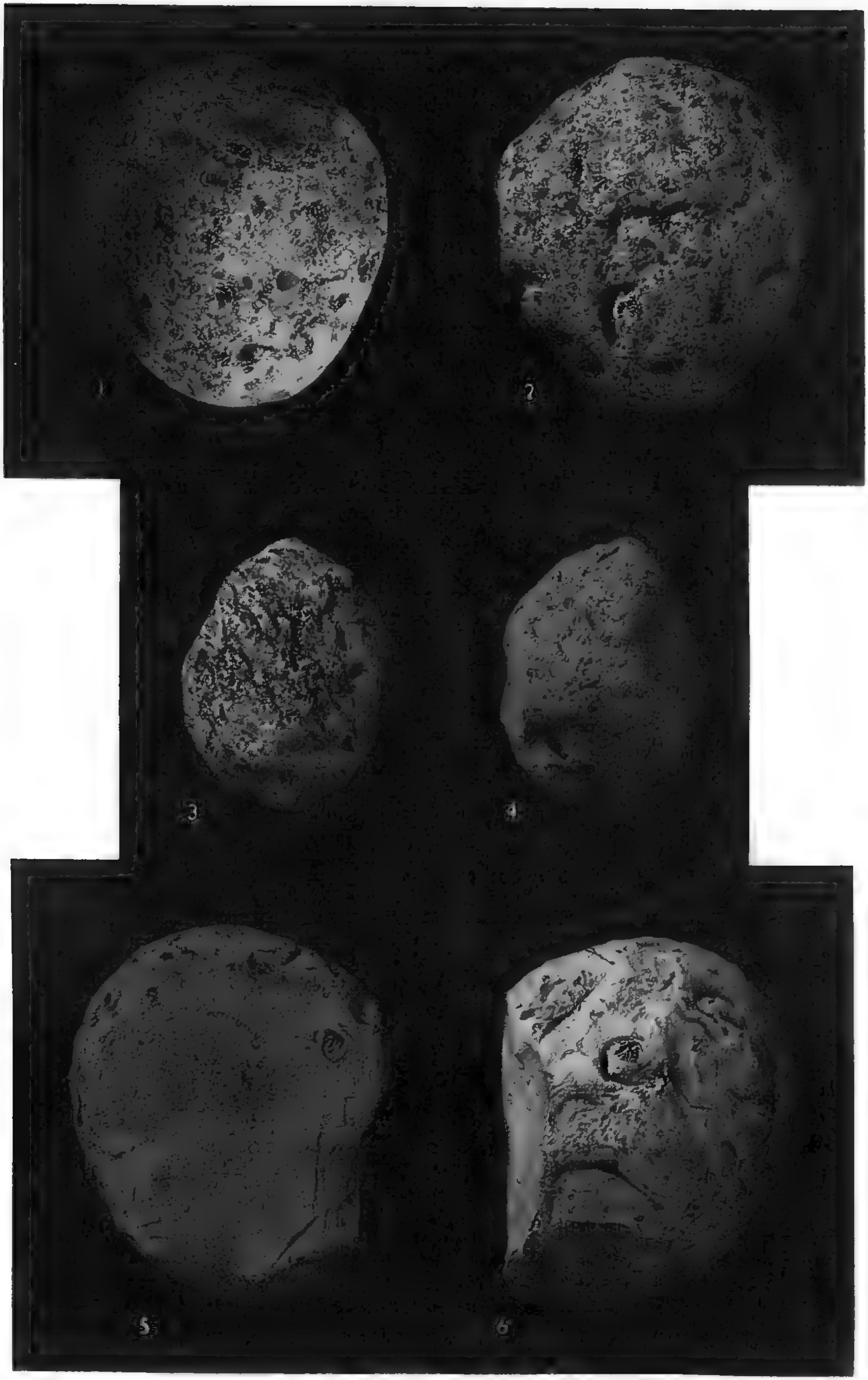


PLATE 7.



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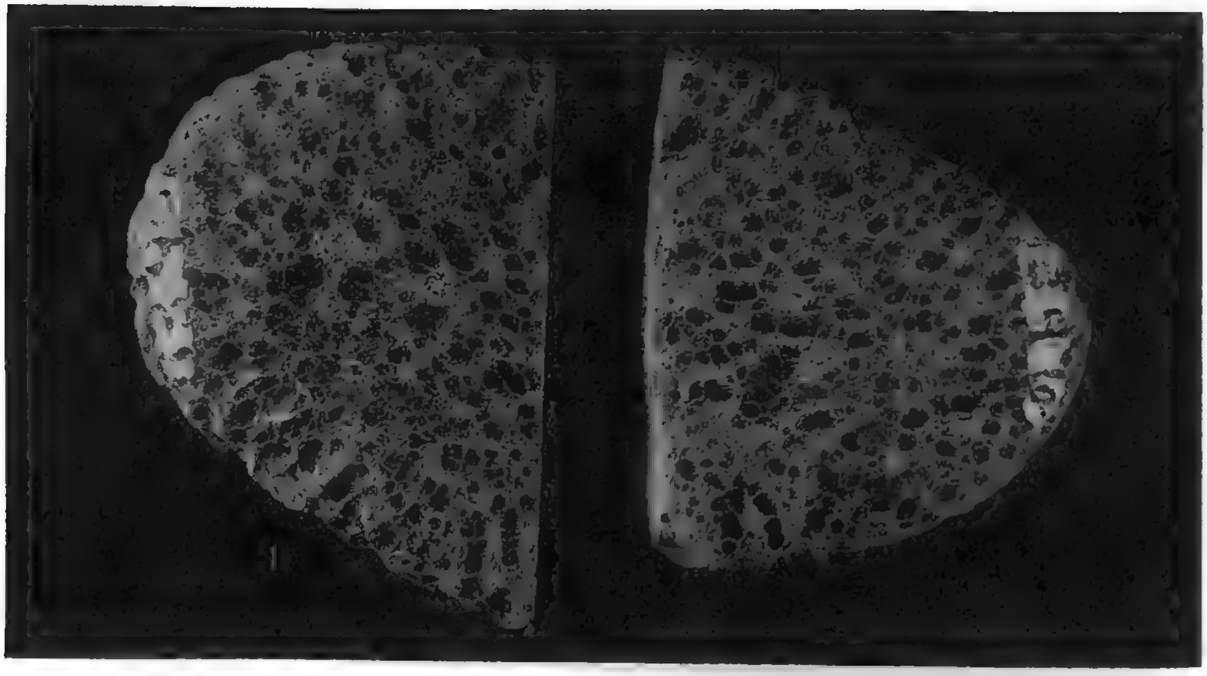


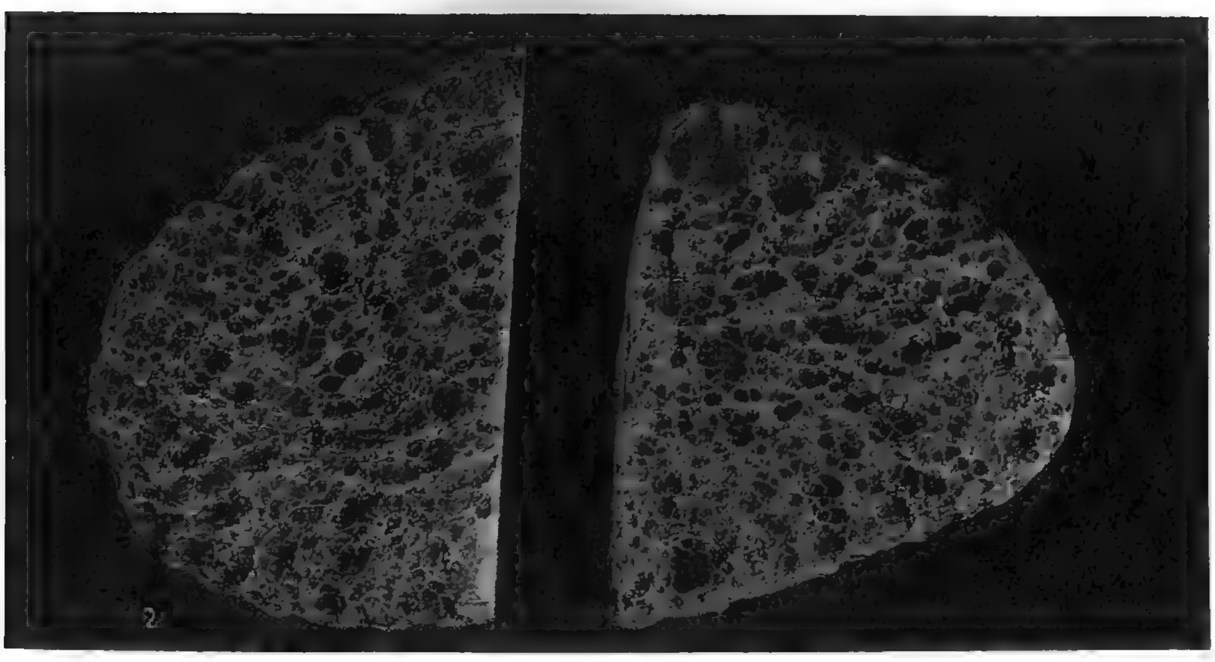
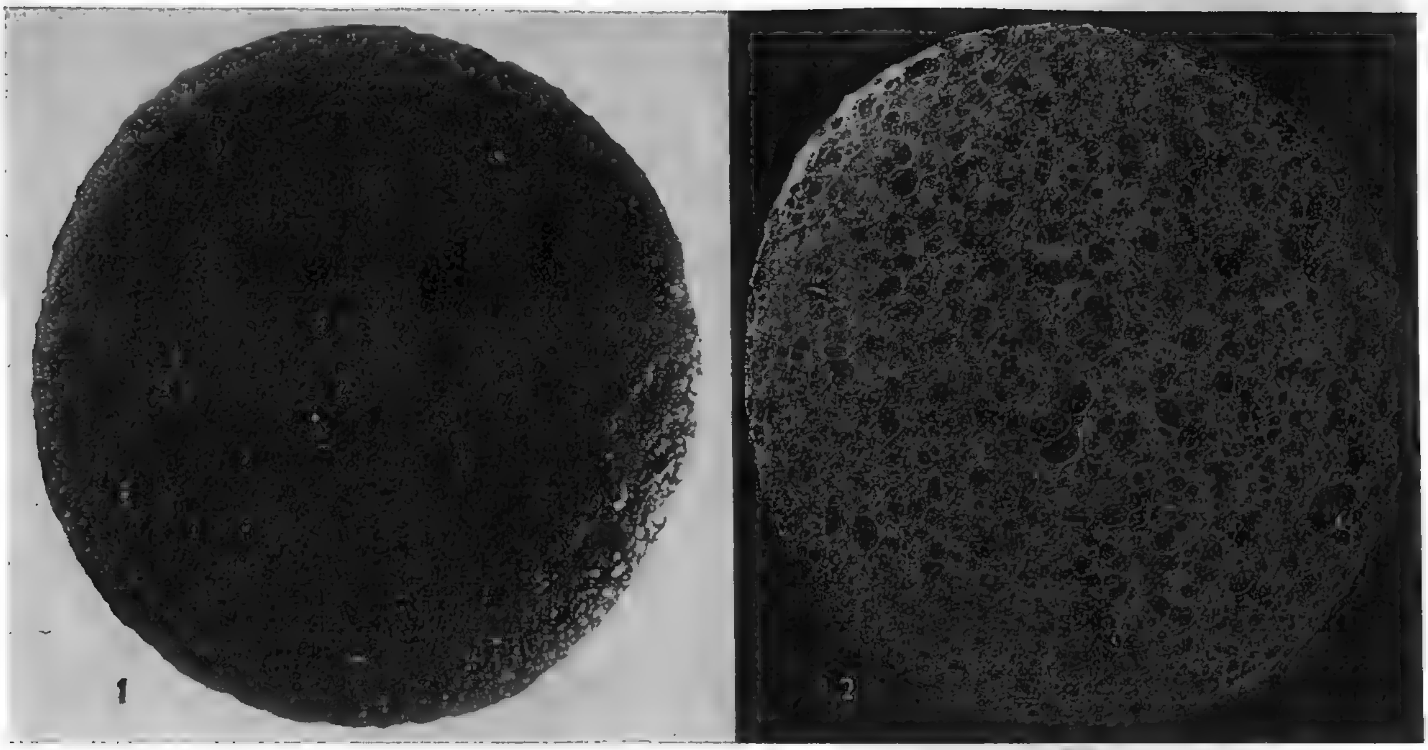
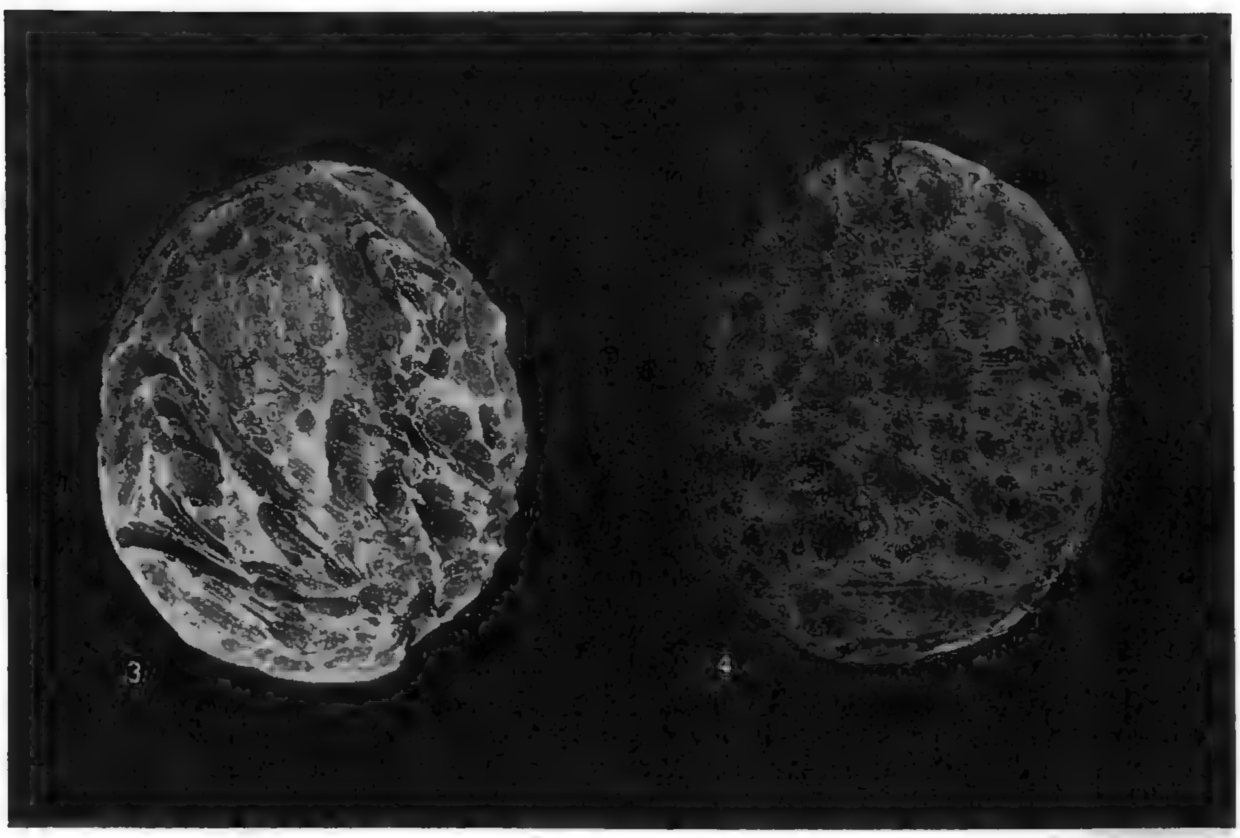


PLATE 9

PLATE 10





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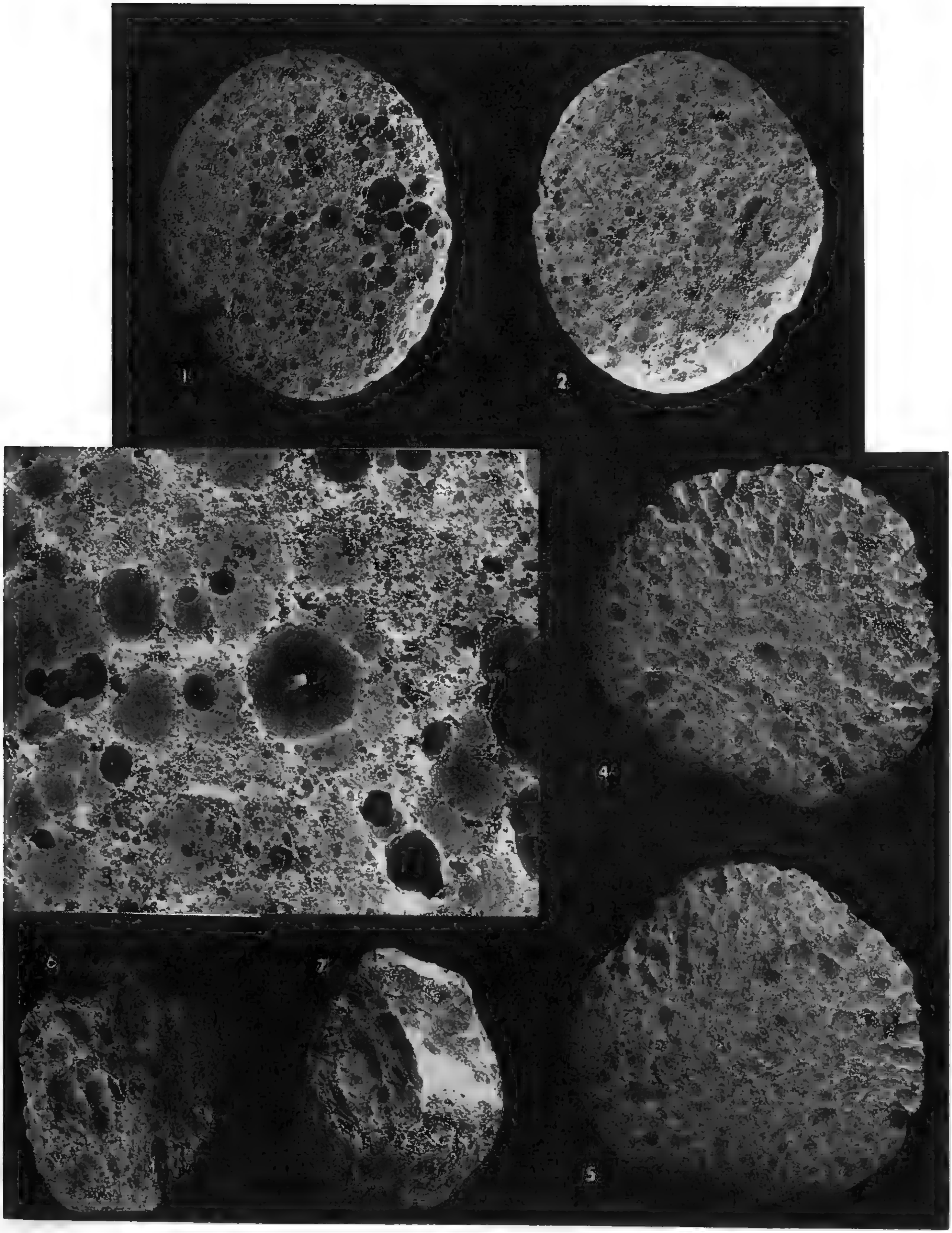

PLATE 12

PLATE 13

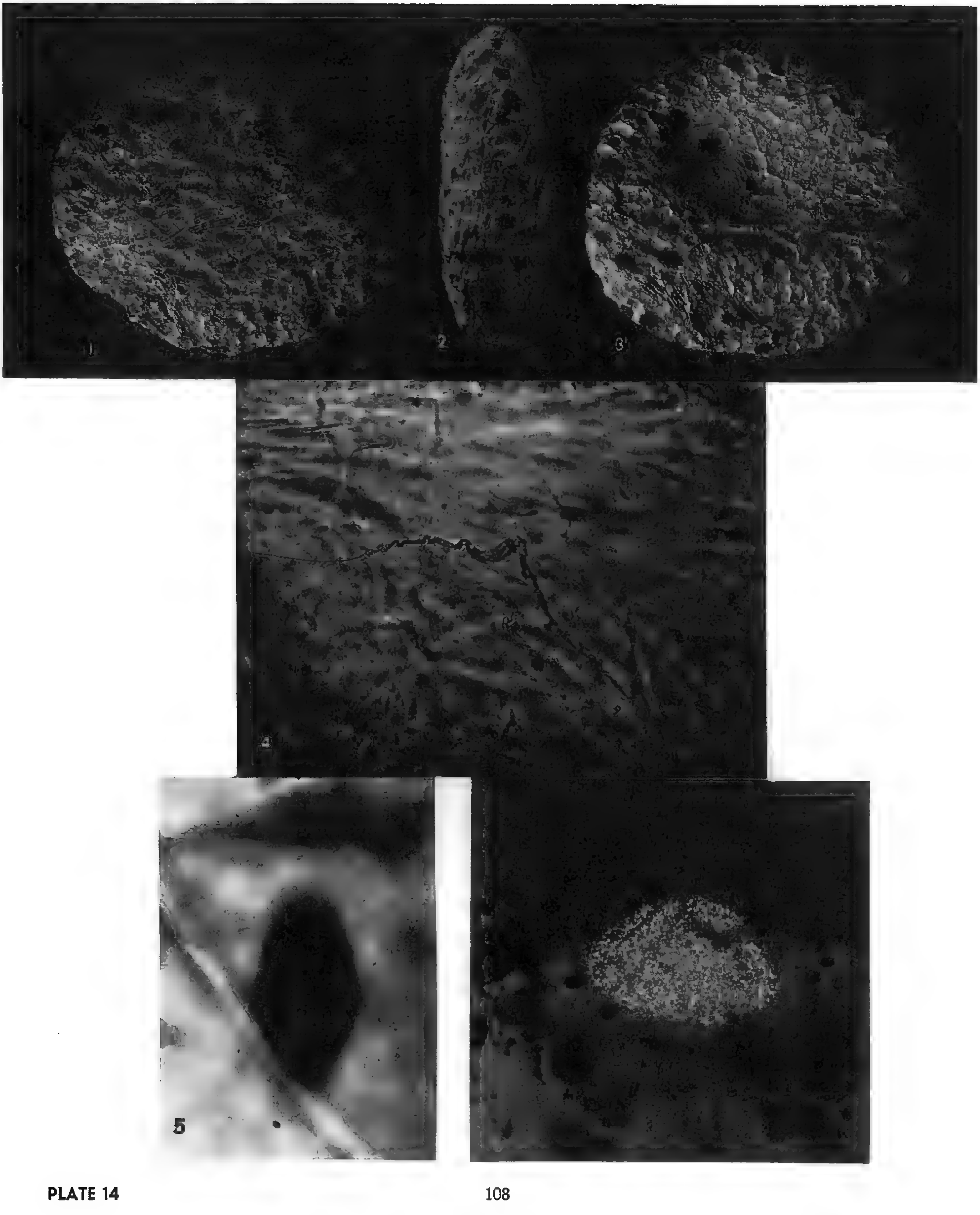

PLATE 14

There is an interesting difference between Georgia tektites and Hawthorn gravels. The tektites are characteristically disk-shaped while the gravels have been described by Cooke (1943) as characteristically angular. The disk shape suggests the possibility of formation by beach erosion. Flattened pebbles figured by Stephenson (1912) from the terrace deposits in North Carolina were regarded as beach pebbles flattened by abrasion on the beach.

A tektite exposed to beach action could become relatively smooth; however, once buried and the movement of sand over it stopped, its surface could have been chemically etched by ground water. The etched surfaces of the Georgia tektites definitely show that they were not moved far from where they were etched. The fact that Georgia tektites with only one exception are complete specimens could mean that they are the few which were washed onto the flood plains where they are being recovered. Nothing, of course, is known about the abundance of tektites on the old erosional surfaces which existed to the west of the Hawthorn beds and no search has been made for fragments of tektites in the gravel lenses within the Hawthorn. Many questions about the geologic history of these specimens remain and require additional study.

Laboratory Studies of Georgia and Related Tektites

The first comprehensive laboratory study of a Georgia tektite was recently published by Clarke and Carron (1961), and their data and conclusion will be summarized in this article. Scarcity of specimen material has been a serious obstacle to investigators working in this field, resulting in an incomplete picture. An important need exists for a number of specimens that can be studied in detail and at least partially consumed. Many questions remain that can only be answered by consumption of small amounts of material in experimental tests. Recently Sumner Wolfson of Boston University made available to us a small quantity of a second Georgia tektite for detailed study.

In early 1960, the Smithsonian's Georgia tektite specimen was under study here and in the laboratories of the U. S. Geological Survey when a tektite find of the previous summer was reported from New England, a new area for tektites. A single specimen was found at Gay Head, Martha's Vineyard, Massachusetts, and the details of that find and a chemical analysis were reported by Kaye, Schnetzler and Chase (1961). It was submitted to us for further laboratory investigation, and the remaining portion is now part of the U. S. National Museum collection (USNM 2082). Investigation revealed that the Martha's Vineyard specimen has many properties remarkably similar to the Georgia tektites. This completely unexpected observation led Clarke and Carron (1961) to suggest that possibly these specimens were either a new group of tektites with exceedingly uniform properties, or that they may be of artificial origin. In the following discussion similarities and dissimilarities will be noted.

Morphology

The Georgia specimen that has been studied in detail is shown in Plate 9, and the Martha's Vineyard specimen in Plate 10. In these photographs the specimens were smoked with ammonium chloride to bring out delicate surface features which otherwise cannot be shown. Plates 11-14 show other Georgia tektites. Table 1 gives dimensions and other physical measurements of these specimens.

A striking feature of Georgia tektites is the prevalence of disklike shapes; three are nearly circular. These specimens are rather uniformly covered with many shallow pits and grooves which produce generally smooth surfaces and edges. The disk shapes are known among moldavite specimens, but are rare among the other tektite groups (Suess, 1900; Barnes, 1940; Baker, 1959).

The Martha's Vineyard specimen appears to be a sector of a roughly circular disk about 3 inches in diameter. The smooth fracture surfaces on the sides of the specimen imply that it has been broken from a parent mass after formation of its surface features. The deeply serrated edge of the Martha's Vineyard specimen is different from Georgia tektites and it is an uncommon feature of tektites in general. The surface relief is also much more pronounced for this specimen. It has sharp ridges on the top and bottom surfaces and particularly on the serrated edge. These sharp, relatively unabraded features imply that the Martha's Vineyard tektite has not been transported far by normal geologic processes subsequent to sculpturing. An unusual feature of this specimen is that the edge pattern appears to be radial, while the surface pattern on the interior of the disk appears to be concentric (Plate 10, No. 1).

It has been stated above that the Martha's Vineyard tektite is apparently a part of a larger disk-shaped object, probably 3 inches (7.6 cm.) in diameter. If this assumption is valid, the parent body of this specimen was larger than any disk-shaped tektite of which we are aware. The hypothetical parent tektite would have a diameter-to-thickness ratio of 7.6, which is greater than that of any tektite known to us. Even if a 2 inch diameter is assumed, this tektite would still

Table 1.—Approximate Size and Weight of Georgia and Martha's Vineyard Tektite Specimens.

Locality	Length of longest axis (cm)	Length perpendicular to longest axis, (cm)	Maximum thickness (cm)	Weight (g)	Density (g/cm^3)	Present Owner	Plate No.
Empire, Ga.[1]	6.5	3.5	1.0	>25	2.33	U.S.N.M.	9
Empire, Ga.	3.3	2.7	1.4	13.4	2.32	U.S.N.M.	11 (3 & 4)
Plainfield, Ga.	3.5	2.9	0.9	11.2	......	G. A. Bruce	12 (1-3)
Plainfield, Ga.	2.3	2.1	1.2	7.05	2.31	L. J. Allen	12 (6-7)
Plainfield, Ga.	3.7	3.4	1.1	16.30	2.34	L. J. Allen	12 (4-5)
Jay Bird Springs, Ga.	4.3	2.1	1.4	14.58	2.33	Ga. Geol. Survey	13 (1-4)
Jay Bird Springs, Ga.	2.8	1.7	0.45	2.60	2.35	Alvin J. Cohen	13 (5-7
Eastman, Ga.	5.1	4.3	1.6	36.5	2.32	U.S.N.M.	14 (1-4)
Osierfield, Ga.	4.7	4.4	0.6	17.8	......	Ga. Geol. Survey	11 (1 & 2)
Martha's Vineyard, Mass.	5.3	3.9	1.0	17.8	2.33	U.S.N.M.	10

[1]Lengths were estimated from photographs of cut specimen, and thickness and density were measured on remaining portion of specimen.

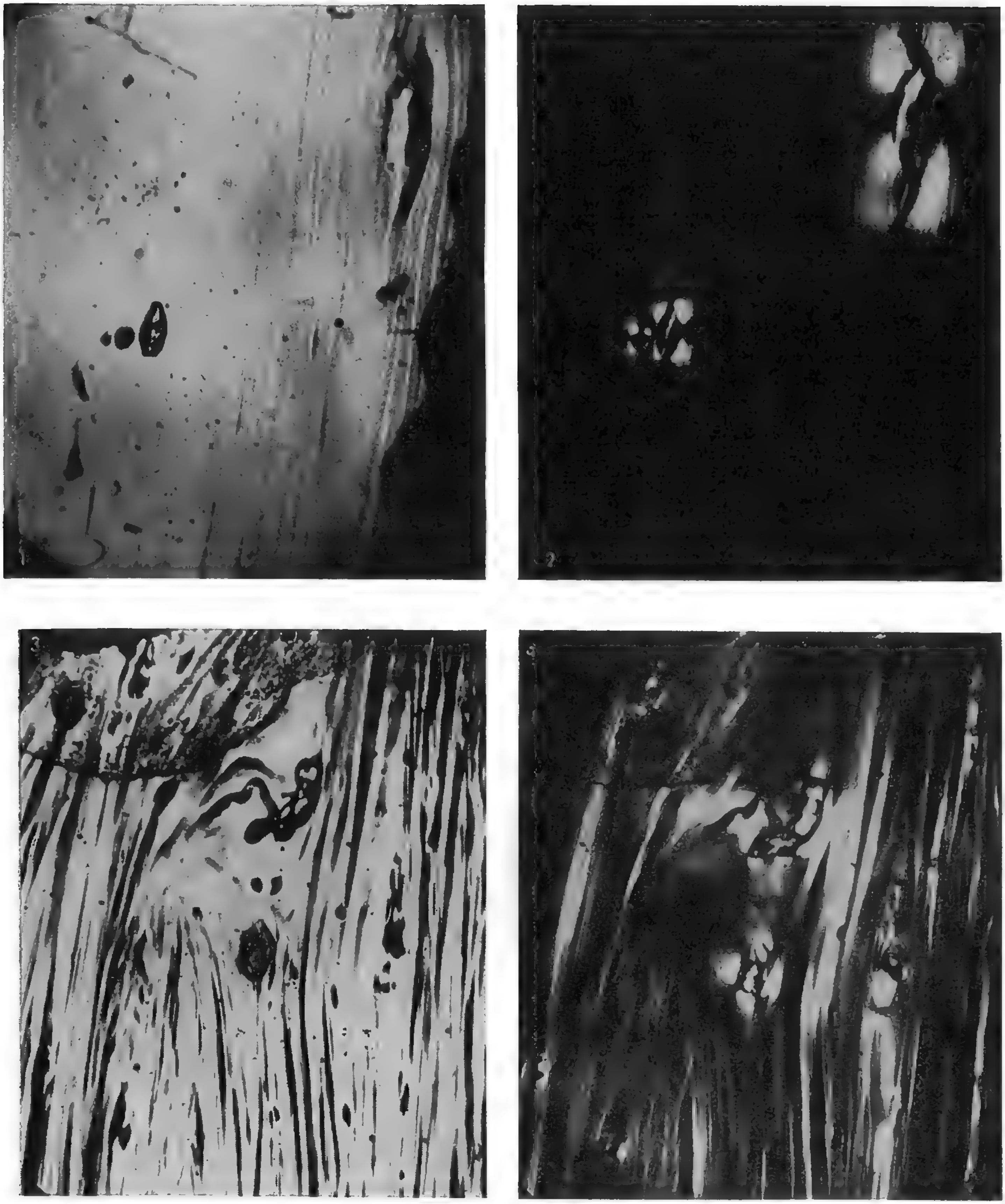

Figure 3.

1, 2 *Photomicrograph of a 0.07 cm. thick slice of the Empire, Georgia tektite, 20 X.*
1, White transmitted light; 2, Crossed nicols.

3, 4 *Photomicrograph of a 0.25 cm. thick slice of Martha's Vineyard tektite, 20 X.*
3, White transmitted light; 4, Crossed nicols.

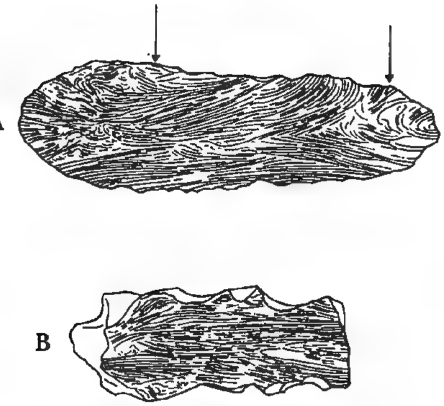

Figure 4. Flow structure diagram prepared from slice of (A) Empire, Georgia tektite, and (B) Martha's Vineyard, Mass., tektite, 1.5 X.

have a very high ratio (approximately 5). The Osierfield, Ga., tektite (Plate 11), with a diameter to thickness ratio of 7, is the only other tektite we know of in this range.

The internal structure and inclusions in the Empire, Ga., and Martha's Vineyard specimens are shown in the accompany photomiocrographs. Fig. 3, No. 1 is a photomicrograph taken with white transmitted light of a slice cut radially from the Martha's Vineyard tektite. Fig. 3, No. 2 is of the same area using plane polarized light, crossed nicols. Fig. 3 no. 3 and 4 are photographs of a slice of the Empire, Ga., tektite. If allowance is made for the differences in thickness between the two sections, the similarity in pattern and character of inclusions is apparent. Some of these inclusions are well outlined and are of lower index of refraction than the surrounding glass. They show wavy extinction and have not been positively identified. Barnes (1940) has proposed that similar inclusions in bediasites are lechatelierite. Sparsely distributed, small, round and elongated bubble cavities are also present, appearing in the photomicrographs as dark spots.

Pronounced flow structure, or flow lines, indicative of inhomogeneity within the glass, appears in both specimens. This structure is revealed by variation in index of refraction resulting presumably from minor compositional differences (fig. 3, nos. 1 and 3). Strain is also present in these glasses and is associated both with the flow structure and inclusions. This strain is evidence from the anisotropism that is observed in the sections with plane polarized light, crossed nicols (Fig. 3, nos. 2 and 4).

The flow structure of both specimens conforms quite well to the surface of the specimens. In Fig. 4 are given flow structure drawings prepared from a projected image of the sections used in making the photomicrographs. This relationship of surface to flow structure is unusual for tektites in general (Barnes, 1940; Baker, 1959).

The present external surfaces of these specimens are essentially secondary features due largely to chemical etching. Indeterminant factors such as the original shape of the specimen, the susceptibility of its various parts to chemical attack, the nature of the chemical environment and the time through which it has acted, and mechanical effects, combined to produce the present surface features of these tektites. The main surface features, pitting and grooving, have no obvious relation to the internal structure of the material. Tektite surface pits are sometimes referred to as bubble cavities, but it is unlikely that bubbles within the glass were responsible for the pitting on the tektites we studied. It has been mentioned above that the bubbles present in the sections were small and sparsely distributed. Their concentration in the glass and their individual diameters are both minute when compared to the surface pits.

The internal flow structure, however, is related directly to delicate striae that are readily observable as a secondary surface feature on these specimens. The striae frequently occur where the flow structure is truncated by the specimen surface and undoubtedly result from slight differences in susceptibility to chemical attack. Striae are obvious on the surfaces of the Martha's Vineyard tektite, (Plate 10), especially on the serrated edge. The second Empire, Ga., tektite (Plate 11) is a striking example of surface expression of internal structure. The more irregular pattern on this tektite probably indicates a more contorted flow structure. Surface striation of this type is also present on the Plainfield (Plate 12) and Osierfield, (Plate 11) Ga., specimens and can be seen in the photographs.

Plate 12, no. 3 is an enlargement of a small area of the surface of the Plainfield, Ga., specimen. It shows several features that are common to all the specimens with which we are concerned and one feature that is peculiar to this specimen. The latter is an apparently glassy mass, or protuberance, that projects from the bottom of a surface cavity (Plate 12, no. 3) and slightly to right of center in Plate 12, no. 1. This protuberance is firmly attached to the body of the specimen and apparently resulted from chemical attack on a volume of glass containing an inclusion or inhomogeneity of more resistant composition.

All of these tektites show what appear to be several generations of surface pits, a feature particularly apparent on close examination of Fig. 14c. Around the right-hand edge of the cavity containing the protuberance there are four outlined depressions, apparently the remnants of previous pits that have grown together and been largely obliterated by the younger central pit. The photograph also shows numerous examples of pits within pits, and pits overlapping pits. A particularly interesting pattern can be seen in the lower left-

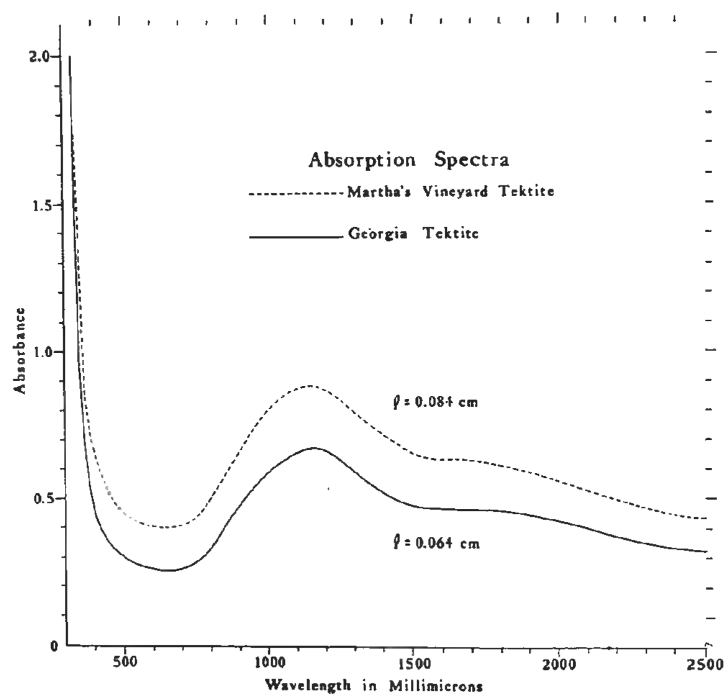

Figure 5. Absorption spectra of the Empire, Georgia, and Martha's Vineyard, Mass. tektite specimens. ƒ is thickness in centimeters of the tektite slice. Absorbance is a measure of the amount of light passing through the specimen. A high absorbance value means that little light passes at the given wave length.

hand corner of Plate 12, no. 3. A raised, rather white area is surrounded by five distinctly outlined grayish areas that seem to have been formed as a result of enlargement of pits. This feature and the glassy protuberance described above provide direct evidence that the internal composition of the material has at least a limited control on the surface features that develop. A number of very small pits possibly could have resulted from bubbles within the glass, but it is impossible to identify any of these from the photograph.

The Eastman, Georgia, tektite (Plate 14) is the largest known specimen, 36.5 grams. It is disk shaped, translucent, and has typical surface etchings and striations. One surface has a thumb size depression (Plate 14, no. 3). Lechatelierite is particularly abundant and many unusually long, contorted streamers can be seen under magnification (Plate 14, no. 4).

The two most recent Georgia tektite finds are from Jay Bird Springs (Plate 13). The larger one (Plate 13, nos. 1-4) is suggestive of a flattened drop and shows typical flow structure and surface features. A particularly interesting feature is the large, elongated bubble that is in the narrow end of the specimen (Plate 13, nos. 2 and 4). It conforms to the direction of the flow structure and is approximately 0.4 mm at its widest diameter and 4 mm in length. There are other smaller bubbles in the specimen that are slightly elongated to essentially spherical. These appear as black spots in Plate 13, no. 4.

The second specimen (Plate 13, nos. 5-7) is interesting in that it is to our knowledge the first tektite fragment to be found in Georgia. It is obviously part of an originally larger object and it shows typical surface etching and flow structure. The broken edge is also etched (Plate 13, no. 6) and reveals flow structure parallel to the surfaces of this thin specimen. It contains few small bubbles and lechatelierite is present. The presence of an unusual flat surface (Plate 13, no. 7), an uncommon feature in tektites, containing three relatively large pits is interesting. This feature could possibly be interpreted as resulting from plastic flow on a flat surface before final solidification.

Physical Properties

A comparison of some of the physical properties of the Georgia and Martha's Vineyard tektite specimens is given in table 2 (taken from Clarke and Carron, 1961). All the properties listed are remarkably similar. The close agreement of density values and chemical compositions (table 3) confirms the impression obtained from transparent sections, that bubble size and distribution in the two materials are the same. The index of refraction values are slightly lower than the lowest value in the range (1.511-1.488) given for bediasites by Barnes (1940) and in the middle of the range (1.480-1.485) he gives for moldavites. The magnetic susceptibility values (Senftle and Thorpe, 1959) depend both on the total amount of iron present and the proportion of oxidized to reduced iron. The slightly higher proportion of oxidized iron in the Martha's Vineyard specimen is consistent with the slightly higher magnetic-susceptibility observed for this specimen. The zero magnetization value, a value which is typical for tektites, in general, means essentially complete solution of iron in the tektite glass. These last two measurements are indicative of a history of high-temperature treatment during formation of the glass. The spectral transmissions of these glasses was also determined and shown in Fig. 5. The broad absorption band at 1150 millimicrons is due to ferrous iron and is characteristic of tektite absorption spectra.

Chemical Composition

The chemical composition of the Empire, Georgia and Martha's Vineyard tektite specimens are remarkably close (table 3). This compositional similarity is further extended by detailed semiquantitative spectrographic analysis reported by Clarke and Carron (1961). Barnes (1960) has reported a chemical analysis for a light green tektite from Fayette County, Texas that is identical in pattern and surprisingly close in quantitative agreement to the Empire and Martha's Vineyard tektites. Barnes (1960) suggests that their material is significantly different from bediasites. It would seem probable that these three specimens have a related origin.

The chemical data on the Georgia and Martha's Vineyard glasses (table 3) fit quite well into the general pattern of tektite analyses as presented by Barnes (1940) in his review of this subject. The moldavites are the only tektite group that have silica contents as high as those obtained in our analyses, and moldavites are the group that are most similar in physical and morphological character to our specimens. It is of interest to compare in some detail Barnes' moldavite analyses to the new data.

Only two of the nine moldavite analyses* have a higher silica content (82.3, 82.7 per cent SiO_2) than the new analyses, and two have essentially the same value (80.5, 80.7 per cent SiO_2), the remaining analyses range from 77.8 to 80.0 per cent SiO_2. The total iron for the new analyses is within the range given for moldavites, but our analyses suggest

*Barnes' analysis No. 5 was excluded from the comparison because of its atypical ferrous to ferric iron ratio and the possibility that this reflects either a peculiar oxidizing history for this specimen or analytical error.

TABLE 2.—Comparison of physical properties of the Georgia and Martha's Vineyard tektites. [a]

Property	Georgia tektite (USNM-1396)	Martha's Vineyard tektite (USNM-2082)
Color	Light olive green	Light olive green
Index of refraction	1.485	1.485
Density	2.330	2.332
Magnetic susceptibility (e.m.u./g.) [b]	3.6×10^{-6}	3.90×10^{-6}
Magnetization	0	0

[a] From Clarke and Carron (1961).
[b] Electromagnetic units per gram.

TABLE 3.—Chemcal Analyses of U. S. Tektites

Elemental oxide	Georgia tektite [a] per cent	Martha's Vineyard [a] tektite per cent	Muldoon, Texas [b] tektite per cent
SiO_2	80.54	80.6	81.31
Al_2O_3	11.21	11.3	10.96
Fe_2O_3	0.33	0.4	0.15
FeO	2.40	2.2	2.29
CaO	0.61	0.7	0.50
MgO	0.65	0.7	0.53
MnO	0.05	0.05	0.03
Na_2O	1.16	1.1	1.50
K_2O	2.38	2.4	2.17
H_2O^-	none	$\angle$0.1	0.02
H_2O^+	0.02	$\angle$0.1	0.03
TiO_2	0.43	0.5	0.53
P_2O_5	......	......	0.01
TOTAL	99.78	99.9	100.03

[a] From Clarke and Carron (1961).
[b] From Barnes (1960).

an appreciably higher proportion of Fe (seven of the moldavite analyses report only FeO). A recent moldavite analyses given by Vorobbev (1960) has a total iron in the expected range with a ferrous-ferric ratio similar to that obtained for the Martha's Vineyard and Empire, Ga., material. Our analyses show a lower proportion of CaO in the alkaline earth fraction, and the total CaO + MgO is only about half of that observed for the moldavites. The total alkalies are within the range given by Barnes, but the proportion of Na_2O is smaller on the average by a factor of slightly greater than 3. These observations relating to chemical composition establish that the Georgia and Martha's Vineyard glasses are significantly different from moldavite glass as we understand it today.

Martha's Vineyard Tektite Inclusion

Although the Martha's Vineyard and Empire, Ga. tektites have many similarities, they have one important difference. The Martha's Vineyard tektite contained an inclusion of a type that has not previously been reported in tektites. This inclusion obviously has an important connection with the origin of this particular specimen, and possibly it has significance for an understanding of the origin of tektites in general. Very little is known about this inclusion at present. However, experimental study continues, and its is hoped that a detailed description will be completed in the near future.

Plate 14, no. 5, is a photograph of the deeply embedded inclusion taken through the surface of the specimen. The apparently opaque central area, or core, is approximately 0.26 mm long and 0.12 mm wide. The dark halo, which gives the impression of a reaction zone, is approximately 1.0 mm long and 0.52 mm wide. The halo is very thin, essentially planar, and conforms to the flow structure of the specimen.

The inclusion was removed from the main mass of the specimen by careful cutting with a thin bladed diamond saw. The resulting small piece of glass was mounted in a Bakelite block in such a way that the long axis of the inclusion was perpendicular to the surface of the block. This mounted specimen was then ground until the interior of the core of the inclusion was reached. This surface was polished, and a photograph of it is shown in Plate 14, no. 6. At this magnification (280x) it is obvious that the inclusion consists of many individual particles which appear to be either minute bubbles or spheres of a glassy material embedded in the glass matrix. Most of these particles lie below the plane of focus of the photograph and their shape is therefore distorted. The halo (Plate 14, no. 5) appears as a light zone extending to the sides of the aggregate in Plate 14, no. 6.

The polished surface of the inclusion was examined by Harry J. Rose, Jr., of the U. S. Geological Survey, by the non-destructive x-ray fluorescence technique. His results show that the area of the inclusion contains major amounts of the chemical element zirconium. Zirconium could not be detected in the matrix by this technique. The semiquantitative spectrographic analyses that were mentioned earlier gave a value of 0.015 percent Zr for both the Martha's Vineyard and Empire, Ga. specimen. The x-ray fluorescence data does not give information on the elements associated specifically with the zirconium. It is impossible with this data to decide if it is present as an oxide, silicate, or possibly in some other association.

The presence of the mineral zircon ($ZrSiO_4$) in the parent material of the tektite is a possible source of this concentration of zirconium. Barnes (1960) has suggested that fused grains of heavy minerals should be observed in tektites, particularly within lechatelierite inclusions, if they are formed from fused rocks of a terrestrial type. However, there is no reason to assume the presence of a concentration of many small zircons in this parent material, and it is difficult to visualize the process that would give the distribution shown in Plate 14, No. 6, starting with a single fairly large zircon crystal.

Clarke and Carron (1961) concluded on the basis of the data then available that a possibility remains that the Martha's Vineyard tektite is of an artificial origin. The information we have at this time on this new inclusion leaves this question open. Stabilized zirconia* crucibles are highly refractory and have been used in the glass industry for a number of years. A small fragment of such a crucible falling into a glass melt could possibly produce a "stone" of the general appearance of that shown in Plate 14, no. 6. An explanation along these lines is, of course, very difficult to reconcile with the 33 million year potassium-argon age recently reported by Dr. Zähringer.

Summary

The tektite problem is undergoing intensive study in various laboratories throughout the world. The great effort that is being made could not be justified if tektites are considered as just another rock type, a rock type that exists in only insignificant amounts. Certainly tektites are the result of an important natural phenomenon. Study of these curious objects will undoubtedly lead to a significantly better understanding of the earth on which we live and of its interactions with extra-terrestrial bodies.

The relationship between Georgia tektites and the other tektite groups is not clear. There is a relationship between Georgia tektites and the Martha's Vineyard tektite, and probably these are related to the Muldoon, Fayette Co., Texas tektites. The relationship between these Muldoon tektites and the bediasites is not settled, although Barnes (1960) has suggested they represent two separate occurrences. This conclusion is hard to reconcile with the observations that the Georgia tektites and bediasites have approximately the same potassium-argon age, and that the Muldoon tektite has a composition very close to the Georgia tektite.

The compositional similarity of the specimens from Mar-

*ZrO_2—stabilizing agent in solid solution.

tha's Vineyard, Massachusetts, Empire, Georgia, and Muldoon, Texas is surprising. There is no reason to expect that the first tektites studied from three localities, approximately equally spaced along an 1800 mile arc, should be so much alike.

It is undoubtedly significant that the Martha's Vineyard tektite contains a unique zirconium containing inclusion, and a search is being made for similar inclusions in tektites from all localities.

The ages of these objects is of great importance, and the potassium-argon method will undoubtedly supply crucial data for an understanding of the origin of tektites. Studies currently being made by Dr. Zähringer in Heidelberg, Germany will considerably extend the amount of this type of data. Possibly these new data will establish a single age for all North American tektites.

Acknowledgments

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Geologic Age of the Tektite Shower and Its Associated Rocks of the Georgia Coastal Plain

by

A. S. Furcron

Geologists deal with the most solid of solid materials, yet interpretations and inferences that can as yet be drawn from these "solid" materials are almost amazingly fluid if not bordering on the nebulous. This observation, although it may sound heretical to some, is borne out by the attempt to date the time of the Georgia tektite shower from the age of the deposits on which they fell.

Tektites are glassy objects of uncertain origin that contain particles of fused quartz. Current theories postulate both terrestrial and extra-terrestrial origin. Artificial glasses, volcanic glasses and fulguritic forms are not believed to be tektites. A review of recent theories with a full table of references has been published (Barnes, 1958). Many students have recently come to accept an impact theory that involves the collision of a large meteorite (?) asteroid or comet with the moon or the earth. The tektites may be material that was thrown far outward after violent explosion far from the impact site; or objects of fused glass shed from the parent body before impact, if they did not come from the moon; and many believe they were deposited almost immediately after their formation. The organization of the National Aeronautics and Space Administration and the recent discovery of coesite related to impact craters over the earth have renewed interest in the tektite problem.

Coesite, a dense stable form of silica produced first in the laboratory by Dr. Loring Coes Jr., was discovered by U. S. Geological Survey personnel at Meteor Crater, Arizona, in 1960. Dr. Eugene M. Shoemaker collected similar glass and "shocked granite" last year from the Rieskessel or Ries Crater of Bavaria. This glass was identified as coesite by Dr. E. C. T. Chao of the U. S. Geological Survey. The presence of coesite associated with other shock effects seemingly validates the meteoritic origin of *such craters even* though meteorites or tektites are not found in their vicinity.

A December 1961 release by the U. S. G. S. (See later page of this issue) indicates that stishovite, a much higher density form of silica where each atom of silicon is surrounded by six atoms of oxygen has been identified from Meteor Crater, Arizona, and the Ries Crater. A photograph of a model of the Ries Crater is published, by courtesy of the United States Geological Survey, on a page following this article. Recent use of the presence of coesite and shatter cones to demonstrate the meteoritic origin of craters over the earth and of peculiar features formerly referred to as "cryptovolcanic" have given encouragement to those who favor an "earth splash" or terrestrial origin for tektites.

Some geologists question the accuracy of the potassium-argon age determinations of tektites. Similarities in composition and physical features are used in denoting the number of showers and in correlating widely separated strewnfields, because although a shower may last an hour or several days even an optimistic geochemist would probably admit that the K-A method may have a minimum margin of error of a million years — thus equal to the entire length of the Pleistocene. But geological methods of determining the age of rocks are more variable in reliability, thus may have a greater margin of error. It is only fair therefore that we also examine carefully our own conclusions upon the geologic age of tektite-bearing rocks.

The following comments are intended to analyze the precision with which geologic interpretations can be applied to ascertaining the geologic age of the "formation" upon which the tektites are found in Dodge and Irwin counties. This "formation" is widespread over earlier rocks of established age, and it is not confined merely to the above-mentioned counties. There has been some tendency to avoid study of deposits upon the Coastal Plain if fossil evidence is lacking; thus more attention to formational mapping, especially of unconsolidated and partially consolidated surficial deposits is desirable.

Some writers seem to infer a close relation between the age of tektites and the rocks upon which they occur, thus a critical examination of evidence for the geologic age of those rocks associated with Georgia tektites is in order. A review of the evidence throws considerable doubt upon the age ascribed to these rocks. It suggests also that the age of tektite rocks in other parts of the world should be studied more critically. When geologists restrict the age of the rocks to definitely accepted limits, and agree upon the formational source of the tektites, and geochemists determine tektite age, much more will be known about their origin, the number of showers, and when they fell.

It is generally believed that our Georgia tektites* are found on or in rocks of Miocene age but potassium-argon determinations indicate that the tektites should have been formed or last heated in Oligocene times. However, the actual age of tektites does not necessarily coincide with the age of the formation which they are in or over. The most recent general interpretation of the surface distribution of the Miocene in Georgia was made by Cooke (1943, p. 89-98) and was published by the Georgia Geological Survey with the Geologic Map of Georgia in 1939. Cooke found that a fine sandy phosphatic limestone composes an important part of the Hawthorn in Florida and South Carolina but wrote that it is less conspicuous in Georgia. The belt of the Hawthorn in Georgia as mapped by Cooke averages about 100 miles in width where it extends through the central portion of the Coastal Plain. It is covered by Pleistocene deposits on the east and it overlies exposed Miocene, Oligocene and Eocene marine rocks on the west. Cooke states "gravel deposits, consisting chiefly of coarse angular pebbles, and sand locally cemented into hard sandstone, are the main constituents of the Hawthorn in a large

The writer wishes to express appreciation to Mr. Robert C. Vorhis, Geologist, U. S. Geological Survey, who read the article and made helpful critical suggestions and editorial comments.

*Mr. Thomas E. Allen of Atlanta has suggested that the tektites of south Georgia be named georgiaites. Mr. Allen has devoted much time and interest to the discovery and acquisition of specimens, which he has donated, with the consent of the owners, to the museums of the Georgia Department of Mines, Mining and Geology. He has given the recently discovered broken specimen from Jay Bird Springs to Dr. Alvin Cohen of the Mellon Institute for geochemical study. Because of Mr. Allen's unselfish interest in tektite studies the term georgiaite is recognized by the Georgia Department of Mines, Mining, and Geology and it is hoped that it will be accepted by later writers.

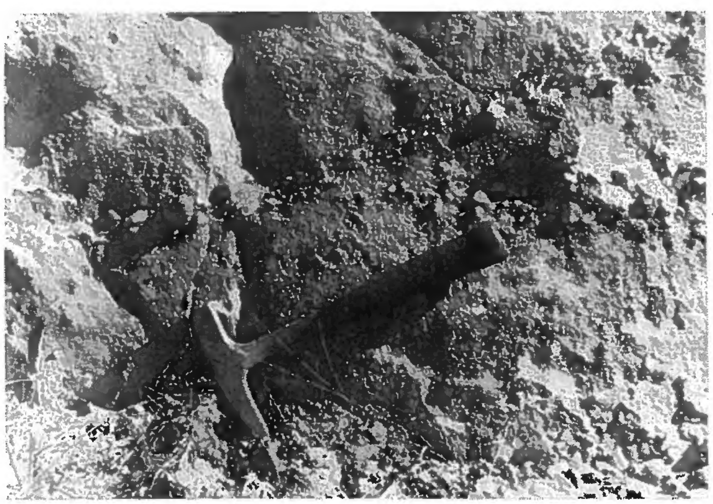
area and comprise the facies to which the name Altamaha grit was originally applied." Thus Cooke is correlating a widespread sand-gravel nonmarine deposit with marine Miocene but the geologic map and bulletin do not indicate where the change takes place. Granting that such a correlation may be reasonable, there is great need for a sufficient amount of detailed work to correlate the Miocene limestones of Florida with such rocks as those which have been called the Altamaha Grit and are included with the Hawthorn of Georgia because there is insufficient detailed mapping available to verify this correlation and measured sections in Georgia do not seem to support it.

These surficial sand and gravel deposits have been described in some detail by an early worker of the Georgia Geological Survey (Shearer, 1917, p. 262):

"The upper portion of the Alum Bluff formation is the so-called Altamaha grit, an extensive deposit of irregularly bedded sands, clays and gravels, locally indurated. The indurated sands and the conglomerates contain a peculiar greenish or greenish-gray disseminated clay and are described as "gray or greenish aluminous grits." The pebbles are predominantly subangular, many of them lath shaped, and the sands are invariably harsh or in sharp angular grains. Feldspar is abundant, and phases may be described as "feldspathic grits." The materials are very coarse grained, even at points 100 miles from their northern margin. The beds that have been locally indurated to sandstones, conglomerates, and claystones do not differ essentially in composition from the non-indurated materials. A negative peculiarity is the total absence of calcareous and fossiliferous materials."

Observed exposures over middle Georgia indicate that this "Altamaha grit" associated with the tektites does not grade downward into limestone but into fullers earth or interlayered sands, gravels and fullers earth even as far south as the Florida line counties (Shearer, 1917, pp. 259-290). Washed well cuttings do not reveal the true composition of such rocks because the clay is lost. Shearer does not describe many sections further north because the fullers earth is generally too sandy or pebbly.

Inasmuch as Pleistocene sands extend from the Atlantic Coast northwestward upon the uplands to an undefined distance it is possible that if the deposit under question is not Pleistocene it may contain upon it Pleistocene deposits which



Sand and gravel beds in rocks associated with the tektites from a cut on U.S. 341, five miles E.S.E. of Jay Bird Springs. Bedding in gravels by unsystematic current action is indicated. Cross-bedding in the poorly-graded sands is evident in the field, but not clear in the photograph. Photo by S. M. Pickering Jr.

are so similar in composition that the two would not be readily separated. In the district under discussion the gravelly deposits with occasional tektites may be Pleistocene or something older, thus, we must admit that detailed study might demonstrate two or even three ages of gravels, the youngest being Pleistocene. Cooke (1943, p. 90) states that "on the east the Hawthorn passes beneath the nearly horizontal coastal terrace deposits." This would make it difficult to separate his Hawthorn from the Pleistocene towards the east or from any possible sandy Pliocene deposits which might occur. A study of depositional features and current directions as indicated by cross-bedding might do much to interpret the stratigraphic succession and thereby to resolve age problems and to indicate source of the sand and gravel.

Since this deposit upon which the tektites are found contains well-rounded quartz pebbles up to fist size in Dodge County, the deposits must have extended much further west because the probable source for this material is the crystalline Piedmont area or reworked Tuscaloosa (Upper Cretaceous). No investigation has yet demonstrated the derivation of these gravels from the Tuscaloosa, but these controversial continental (Miocene?) deposits must formerly have covered almost the entire Coastal Plain, and may have extended over the Tuscaloosa into the southeastern Piedmont. Should a tektite be found as closely associated with our upper Cretaceous as is the Martha's Vineyard find it would not be out of order in our present state of knowledge to theorize that it had been "let down" into these older sands, gravels and clays after erosion.

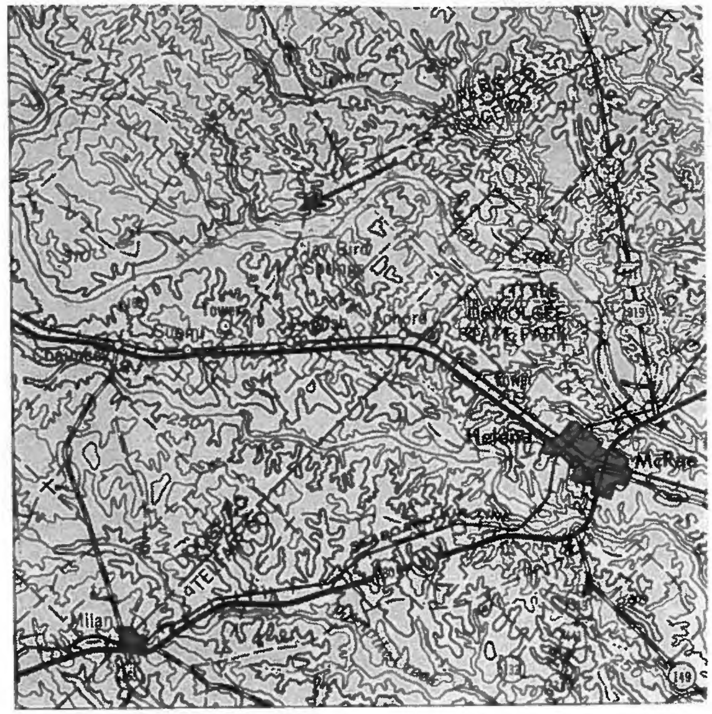
In Pulaski County a post-Cooper Marl formation (Oligocene) composed of clay, chert, and iron ore residuum unconformably underlies the sand and gravel (Pickering, 1961). In Dodge County it has not been recognized in the strewnfield because regional dip carries it under rocks exposed by erosion. Well logs from Coastal Plain counties east and southeast of this district show unfossiliferous sandy arkosic material with clay from the surface downward to recognizable fossiliferous Miocene limestone (Herrick, 1961). This overlying material undoubtedly includes the same deposit that is mapped and referred to as Hawthorn by Cooke or as Altamaha Grit by earlier writers. Thus southeast of the tektite area, and under the wide belt of debatable sand, gravels, clay and fullers earth marine Miocene does overlap the Oligocene. But is this Miocene stratigraphically correlative with the sand and gravel? This is an important consideration because it seems to be the only basis for including these surficial deposits with down-dip Miocene Hawthorn.

The gravels are distributed locally through sands and clays from bottom to top; there may be a few thin gravel beds or the gravel beds may be numerous and several feet in thickness. Deposits are cross-bedded, deposited by current action, and show every indication of being unconformable upon the underlying Tertiary deposits. The unconformity at its base is a notable one if we consider the source and composition of the overlying materials and their mode of emplacement.

The tektites are found on the surface of this deposit and in no case, thus far, do we have a record of one of them being found in undisturbed originally-deposited material.* Most of the specimens found to date have come from cultivated sandy fields on the upland surface. The two georgiaites picked up at Jay Bird Springs were hauled down from gravel deposits which are on the surface above the valley west of the Springs. Some found in sandy fields near old dwellings may have been hauled there from gravel pits, but gravel

*The long axis of the strewnfield is normal to regional strike thus suggesting that the tektites fell *on* the surface rather than in the formation.

Gravel pit on the upland above Gum Swamp Creek, Dodge County. It is believed that the two Jay Bird Springs tektites were trucked from here. This loose gravel and sand is brown and current bedded a few feet below the surface, and appears to be equivalent to "Hawthorn" beds well-exposed in highway cuts about 100 yards to the left (west) of the view. The lake in the foreground is artificial. Photo December 1961.



Section of the Macon, Georgia quadrangle U.S.G.S., scale 1:250,000 showing location of gravel pits above Gum Swamp Creek from which the Jay Bird Springs tektites are believed to have been removed.

beds and sand in place occur in road cuts and gulleys also at the same localities.

The possibility that these tektites fell on Pleistocene to Recent rocks must be considered. Thus far all of the tektites except the two at Jay Bird Springs have been found in fields where the soil has been disturbed; thus no exact relationship can be determined. Both of the Jay Bird Springs tektites were discovered by Mr. Will Sellers of Helena who turned them over to Tommy Bland of the same town and it was from Mr. Bland that Thomas E. Allen received them. Around the camp at Jay Bird Springs numerous loads of quartz gravels were hauled and all of them came from a gravel pit on the upland north of Gum Swamp Creek. Inasmuch as this pit is near the creek, the gravels were reinvestigated in order to discover any further clue regarding their origin. The upper gravels are whiter and tan iron stain has been removed by the action of carbonaceous material in the soil, but excavation in the pits indicates that they are the same gravels and sand which crop out on the highway nearby. The new road cuts on this highway offer good fresh cross-sections of the rocks. Below exposed top soil there are gravels mixed with sand and beneath them clay and sand with some gravels. In the ditch there is a layer of green clay or fullers earth which contains gravels up to the size of beans. The material is cross-bedded, roughly stratified, although sand and gravel is poorly sorted and is mixed in a more or less promiscuous manner. Approximately 35 feet of these rocks are exposed here. There is nothing to indicate that they differ from the other rocks referred to by Cooke as Hawthorn. These gravel "pits" are scattered over uplands all over the county and there is need for a more detailed type of study in order to discover if there may be local upland Pleistocene deposits which have been generally classified with the other rocks. Aerial photographs would be necessary to such a study because topographic maps have not been prepared.

There are numerous reasons for believing that tektites were not water-transported. They are not beach deposits because they are not eroded or broken and are with rounded quartz pebbles. The strewnfield extends into Irwin County near the mid part of the sand-gravel belt with no specimens found to date in gravels on either side. They seem to be too fragile to have withstood rapid transportation with rough sand and quartz pebbles. Except for some minor fresh chipping, only one broken specimen has been found (the recent Jay Bird Springs find). The broken surface is chemically etched but not eroded by transportation, thus the specimen should have fallen where it was found. Occasional fresh chipping may be traced to mishandling or by being carried around in the pocket after discovery. These tektites are under strain thus fragile, and several examined by the writer all give a biaxial interference figure with a symmetrical pattern which argues against unequal wear by transportation. Because rock ages and tektite origin are not agreed upon, their age at the time of emplacement relative to that of the formation is not known. However, if they are found where they fell, and the geologic age of the formation is determined, the date of the fall is known within limits.

Similarities of bediasites (Texas) and georgiaites in age and appearance cause some workers to believe that both belong to the same "fall," (Cohen, 1959). That fact would not positively correlate these two widely separated surficial deposits unless it can be shown that the tektites (from both localities) were not actually transported by water to the positions in which they were found. Georgiaites are found with deposits which are over Oligocene rocks, but Barnes (1961) believes that the bediasites are from Eocene rocks.

The solution of the "tektite problem" does not seem to be advancing upon an even front, and field geology appears to lag behind other aspects of the investigation. However, more dependable geological age determinations of formations associated with tektites will play a useful part in establishing an acceptable theory for their origin.

It is difficult to determine the geologic age of unconsolidated, nonmarine, surficial sand and gravel deposits south of the limits of Pleistocene glaciation. Barnes, (1961, p. 63)

published a table showing the age of tektites over the world based on the geologic ages of the rocks in which they are found. The georgiaites and the debatable Martha's Vineyard find are not included. All of them are Pleistocene to Holocene except the Texas bediasites of Eocene age, and Bohemian moldavites of middle Miocene age. All of the tektites in this country have a K-A age indicating Oligocene. However, if they fell at the same time it would be unlikely that they would all fall upon Oligocene rocks or even rocks of the same age. Geologists report them all from rocks of different ages. The actual age of the javaites and the last two types above was also determined by the K-A method, but how conclusively have the ages of the associated deposits been determined geologically?

We have not established the age of rocks associated with georgiaites, and Barnes writes (1939, p. 551) for those of Grimes County, Texas, "on the surface and above the Jackson old siliceous gravels are found and associated with these gravels are the bediasites." These gravels are supposed to be Eocene to Plesitocene by various writers (Barnes, 1939).

In a recent publication Barnes (1960, p. 337-8) writes that "most bediasites are aligned along the outcrop of the Bedias sandstone, which is in the lower part of the Jackson group. Most of those in Fayette County and adjacent counties to the southwest are on the outcrop of the Whitsett beds, which form the top member of the Jackson group." He believes that this difference in distribution and notable differences between the two varieties of tektites, suggest two separate showers, the younger of which may correlate with tektites in Georgia. The Jackson is Eocene but K-A determinations on bediasites and georgiaites give them the same age of approximately 30 million years.

The Martha's Vineyard tektite was found (Kaye, et al, 1961) on early Late Cretaceous rocks, but could have weathered from a cliff from Late Cretaceous, Miocene or Pleistocene rocks. This tektite is also 30 million years old.

Foreign observers appear to be casual about the geology of the unconsolidated materials which contain the moldavites. In Dr. Barnes' review of the literature he cites observers who state that they are: in sands and soils; in conglomerate gravels on Tertiary rocks, in quartz gravels on hilly plateaus 50-100 meters above the flood plain of Moldau River; on gravels of Pleistocene or Tertiary age; and on middle Miocene deposits.

If the georgiaites, bediasites and moldavites are in or on Pleistocene deposits then all of the important world showers are Pleistocene to Recent. We will then have young and old tektites all on young rocks. That would infer that *some* tektite swarms are thrown into orbit and remain there millions of years before they fall; and their bright, fresh, unweathered appearance and constant association with the surface indicate that they did not fall very long ago. But, if the geological age of associated rocks and present tektite K-A age determinations can be brought into accord and relied upon for the above-mentioned occurrences, then from both types of evidence we may have had three periods of tektite showers in Tertiary to Recent times, i.e., the georgiaites, bediasites, and Martha's Vineyard (31-33 million) moldavites (11 million) and the recent tektites (Pliocene?-Pleistocene). If these old tektites did fall late, then probably geologists have encountered difficulties in separating surficial Pleistocene gravels and sands from similar unfossiliferous Tertiary deposits. In this connection, a careful comparative study of the physical and chemical features of the old European and American tektites versus the much younger ones of Southeast Asia, Australia and Africa, would be in order. Moldavites, bediasites and georgiaites have striking similarities (Cohen, 1959; Barnes, 1960; Clarke and Henderson, 1961). Geologic ages of surficial deposits associated with the older tektites should be re-examined.

There is insufficient evidence at present to derive conclusions on the age and relations of the formation in Georgia to its associated tektites. These sands, gravels and sandy clays are unconformable above weathered and slumped marine clays and limestone residuum of middle Oligocene (Flint River of Cooke, 1943). For earlier geological controversies upon the possible ages of these rocks see also Wilmarth (1938) for references to the Lafayette Formation and the Altamaha Grit. Until geologists can come to generally accepted conclusions regarding their age or ages, it may be best to assign them to the tentative age of Pliocene-Pleistocene.

Thus the geological opinions of numerous workers indicate that these debatable deposits may have any of the following possible geologic ages:

1. Upper Oligocene. This would require bracketing overlying unfossiliferous continental type deposits in central Georgia Coastal Plain with a marine Oligocene limestone residuum from which it is separated by an unconformity. Also the deposits are known to overlie marine Miocene elsewhere. (See 2 below). Thus combinations 6, 7 and 8 below are not regarded seriously.

2. Miocene. The deposit is reported to grade into marine Miocene to the east (Cooke, 1943) and overlies marine Miocene to the east as determined from well logs (Herrick, 1961), and this should be the Tampa equivalent. It overlies marine Tampa Limestone (Miocene) (Cooke, 1943.) along the Pelham Solution Escarpment east of Flint River. As mentioned previously, it (Cooke, 1943) overlies marine Miocene, Oligocene, and Eocene along the western exposed margin of the belt, which is inference for believing that it is unconformable upon all of them. A thin marine mixture of sand and shells (Duplin Marl) of Miocene age is reported to be unconformable on sediments mapped as Hawthorn in the lower Savannah basin (Cooke, 1943, p. 98-100). Do not these various observations suggest that the sand, gravels and fullers earth here under discussion may be something younger than Miocene thus not at all equivalent to the marine Miocene? Age determinations make the tektites too old for Miocene unless they spent some time in orbit.

3. Pliocene. Veatch and Stephenson, 1911, referred to it as the Altamaha Formation which they tentatively assigned to Pliocene(?); also they believed a part of it equivalent to the so-called Lafayette(?) Formation.

4. Pleistocene.
5. Pleistocene on Pliocene.
6. Pliocene on upper Oligocene.
7. Pleistocene on upper Oligocene.
8. Pliocene and Pleistocene on upper Oligocene.
9. Pliocene on Miocene.
10. Pleistocene and Pliocene on Miocene.
11. Pliocene and/or Pleistocene on Miocene (MacNeil, 1947, just east and south of the tektite counties).
12. Pleistocene on Miocene (Cooke, 1943, just east of the tektite counties).

Conclusions

The above review indicates that the georgiaites fell on or possibly in the sands and gravels where they are found, and although these deposits may not all be of the same geologic age, if the geochemists are correct, the tektites are older. The tektite shower post dates the Oligocene, and although geological interpretations are conflicting, there is sufficient evidence to suggest a probable Pliocene-Pleistocene age for the fall.

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